*Chapter 5*

# EXPERIMENTAL RESULTS AND DISCUSSION

## 5.1 DATA GATHERED

Two repair schemes were evaluated in this study. The first involved repairs where no concrete was removed and only a surface treatment was applied. Some specimens were treated with an epoxy coating, silane sealer, polymer (resin) coating, or CFRP composite wrap. The second repair scheme involved repairs where portions of concrete were removed and replaced with a patch material (see section 4.6 for the test plan details).

The corrosion current was monitored continuously throughout the duration of the accelerated corrosion regime with a data acquisition system. In addition, periodically, half-cell potential readings were obtained. The half-cell measurements were only taken on the non-treated beam-ends since surface treatments provide a non-conductive barrier that renders the half-cell measurements ineffective. A contour plot of the gathered data was developed for each region.

Expansion measurements were also periodically taken at each beam-end. The expansion measurements were compared to readings taken from unexposed and untreated 4-inch and 6-inch cylinders, as well as a metal bar. However, due to problems encountered with the metal points corroding, the accuracy of the measuring device, and issues with keeping the points attached to the concrete surface, it was determined that the readings were inconsistent and not representative of accurate strain measurements.

The specimens were visually monitored for cracking and spalling. Detailed crack maps were sketched at the end of the first 6-month corrosion exposure cycle and at the end of the 1 ½-year exposure program. The widths of the cracks were measured using a crack width comparator. Chloride measurements were taken before exposure to chlorides, after 6 months of exposure, and at the conclusion of testing. The beam-ends were dissected and prestressing strands were exposed after a total of approximately 18 months of accelerated corrosion and exposure to chlorides.

### 5.1.1 Concrete Material Data

The measured slump of the concrete was 7 ½ inches. The average measured compressive strengths were 6598 psi at release of the tendons and 7530 psi after 28 days. Tables 16 and 17 summarize the average compressive strength results for the concrete cylinder samples. Complete test results are listed in Appendix C.

Table 16. Concrete Cylinder Average Compressive Strength at Release*

| Date | Age (days) | Cylinder Size (inches) | Sample Size | Mean (psi) | Standard Deviation (psi) |
|---|---|---|---|---|---|
| 01/10/02 | 1 | 4x8 | 8 | 6317 | 1771 |
| 01/10/02 | 1 | 6x12 | 2 | 6598 | N/A |

Table 17. Concrete Cylinder Peak Compressive Strength*

| Date | Age (days) | Cylinder Size (inches) | Sample Size | Mean (psi) | Standard Deviation (psi) |
|---|---|---|---|---|---|
| 02/07/02 | 28 | 4x8 | 8 | 6522 | 1326 |
| 02/07/02 | 28 | 6x12 | 2 | 6012 | N/A |

* Test results provided by Spancrete, Inc. (manufacturer)

### 5.1.2 Chloride Content

The chloride content of the unexposed beams was determined by analyzing pulverized concrete samples at various depths using Rapid Chloride Test (RCT) 1029 method [21]. The RCT measures the acid soluble amount of chlorides as a percentage of concrete mass. A specified amount of chloride powder was extracted and mixed with a vial containing 10 mL of extraction liquid. A potential reading was taken with the RCT chloride electrode and then converted to chloride content in percent of concrete weight using the provided calibration chart. The same procedure was followed for determining the chloride content after the first cycle of saltwater exposure and at the conclusion of the 18-month test period. The initial chloride sample (before accelerated corrosion) was taken at the center of one beam. Table 18 summarizes the collected chloride content data before application of the accelerated corrosion regime. (Please see Appendix D for complete chloride data.) The average depth shown in Table 8 refers to concrete powder collected from a distance of ±1/8 inch of the average depth. For example, the chloride content at average depth of ±½ inch refers to powder collected from depths ranging between 3/8 and 5/8 inches. The reasonably uniform readings indicate that chlorides were present in the concrete at time of mixing.

Table 18. Initial Chloride Content of Prestressed Concrete Beam

| Average Depth (inches) | Chloride Content (% by weight of concrete) |
|---|---|
| 0.25 | 0.035 |
| 0.50 | 0.051 |
| 0.75 | 0.041 |
| 0.875 | 0.055 |

The measured chloride content of the concrete prior to corrosion testing was relatively high (Table 18). Therefore, a number of previously unplanned tests were performed to identify the source(s) of chlorides. The chloride content of the mix water was tested with the RCT method to determine if the water used in the concrete mix was the source of chlorides. The chloride content of the 300 mL sample of Green Bay water was found to be 0.0017%. A sample of water from Milwaukee was also tested for comparison purposes and was determined to have a chloride content of 0.0014%. Therefore, the chloride contents of both water samples were relatively equal and contained a negligible chloride concentration.

A sample of coarse and fine aggregates that were utilized in the construction of the beams were obtained and tested. The acid- and water-soluble chloride contents of the coarse aggregate samples measured were 0.041% and 0.035% by weight of aggregate, respectively. The measured acid-soluble chloride content of the sand was 0.039%. These results indicate that the aggregates were the likely source of the relatively high levels of chlorides measured in the new concrete.

Chloride samples following the first 6 months of the accelerated corrosion regime were taken at two locations on the bottom flange of the beam-end receiving the patch repair. The measurements were taken at various distances from the surface, 2 and 6 inches from the back end of the beam. Table 19 summarizes the collected chloride content data after application of the first exposure cycle.

Table 19. Chloride Content of Prestressed Concrete Beam After First Exposure Cycle

| 2 inches from End of Beam On Bottom Flange | | 6 inches from End of Beam On Bottom Flange | |
|---|---|---|---|
| Average Depth (inches) | Chloride Content (% by weight of concrete) | Average Depth (inches) | Chloride Content (% by weight of concrete) |
| 0.25 | 0.96 | 0.25 | 0.21 |
| 0.50 | 0.74 | 0.50 | 0.29 |
| 0.75 | 0.47 | 0.75 | 0.188 |
| 1.00 | 0.29 | 1.00 | 0.135 |

The measurements indicate high chloride concentrations near the surface, with the values decreasing with increasing distance from the surface. This is consistent with the behavior of chloride ions migrating into the concrete. Figure 27 illustrates the comparison of the collected chloride content data.

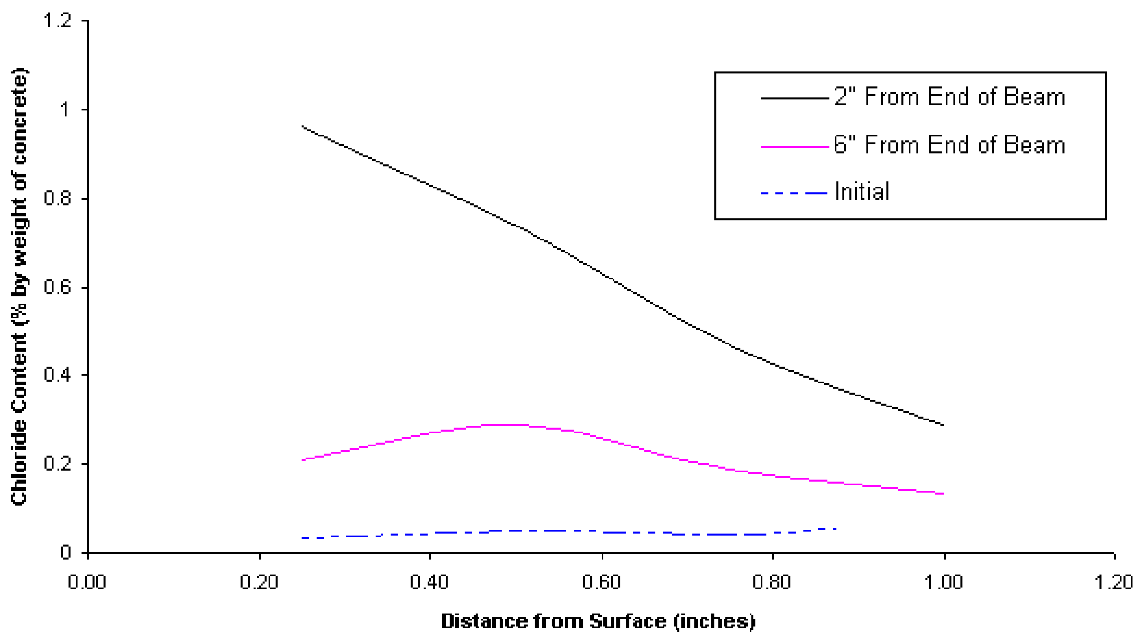



Figure 27. Comparison of Chloride Contents – Phase I

Research conducted by Lewis [26] suggests that the corrosion threshold value is 0.15% of acid soluble chloride by weight of cement. ACI Committee 222 [52] recommends the corrosion threshold value of 0.2% acid soluble chloride by mass of cement. Recently, other researchers have suggested a large variation in the corrosion threshold. In either case, the currently utilized corrosion threshold is exceeded at all depths measured at a distance of 2 inches from the end of the beam. At the location of 6 inches from the face of the beam, the corrosion threshold level is exceeded up to a depth of ½ inch.

Chloride samples were also taken at all beam-ends at the conclusion of the entire 1 ½-year exposure prior to dissection. These measurements were made on samples taken in the middle of the sloping surface of the bottom flange at a distance of 2 inches from the back of the beam. Tables 20 through summarize the measured chloride contents on all beam-ends.

The highest chloride levels are observed in the beam-end with patch repairs. Acid-soluble chloride levels are on the order of 1.0% by weight of concrete is measured at depth of up to 1.0 inch. It appears that the interface between the old and new concretes may have allowed accelerated intrusion of chlorides deep into the patch and old concrete.

The chloride contents for the beam-ends that were treated with epoxy coating, polymer resin coating or FRP from day 1 clearly show significantly lower chloride contents than other specimens. The beam-end treated with Silane sealer from the first day had far less chlorides than the untreated beams (or beams treated after 6 months). However, the chloride levels for this beam-end were higher than the corresponding beams treated epoxy coating, polymer resin coating or FRP from Day 1.

The specimens that were treated after 6 months show high levels of chlorides, but they are less than the beam with patch repair. It should be noted that comparisons between measured chloride readings should be done in light of the fact that the chloride levels can vary statistically from point to point (even on the same beam at the same relative locations). Therefore, precision implied by the measurements at one location may be misleading, unless differences observed are significant.

The untreated beam-end 2A shows smaller chloride contents than expected. However, as noted in the corrosion current section of this report, a loose electrical connection may have somewhat reduced the corrosion potential to this beam end, thus explaining the lower –than-expected measured chloride content.

Table 20. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 1A (Epoxy Coated from Day 1)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.071 | 0.072 |
| 0.50 | 0.058 | 0.058 |
| 0.75 | 0.057 | 0.058 |
| 1.00 | 0.080 | 0.081 |
| 1.25 | 0.070 | 0.072 |
| 1.50 | 0.075 | 0.078 |

Table 21. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 1B (Epoxy Coated after 6 Months of Exposure)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.780 | 0.740 |
| 0.50 | 0.620 | 0.640 |
| 0.75 | 0.240 | 0.240 |
| 1.00 | 0.260 | 0.285 |
| 1.25 | 0.170 | 0.190 |
| 1.50 | 0.105 | 0.110 |

Table 22. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 2A (No Treatment)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.830 | 0.840 |
| 0.50 | 0.460 | 0.465 |
| 0.75 | 0.205 | 0.215 |
| 1.00 | 0.105 | 0.110 |
| 1.25 | 0.140 | 0.145 |
| 1.50 | 0.100 | 0.100 |

Table 23. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 2B (Patch Repair After 6 Months of Exposure)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 1.018* | 1.018* |
| 0.50 | 0.750* | 0.750* |
| 0.75 | 0.963* | 0.981* |
| 1.00 | 0.921* | 0.965* |
| 1.25 | 0.744* | 0.710* |
| 1.50 | 0.695* | 0.709* |

Table 24. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 3A (Silane Sealer From Day 1)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.132 | 0.143 |
| 0.50 | 0.061 | 0.074 |
| 0.75 | 0.077 | 0.084 |
| 1.00 | 0.068 | 0.084 |
| 1.25 | 0.046 | 0.057 |
| 1.50 | 0.101* | 0.103* |

Table 25. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 3B (Silane Sealer After 6 Months of Exposure)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.430 | 0.430 |
| 0.50 | 0.225 | 0.225 |
| 0.75 | 0.105 | 0.105 |
| 1.00 | 0.181* | 0.184* |
| 1.25 | 0.134* | 0.136* |
| 1.50 | 0.127 | 0.133 |

Table 26. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 4A (polymer Resin Coating After 6 Months of Exposure)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.840 | 0.870 |
| 0.50 | 0.500 | 0.510 |
| 0.75 | 0.350 | 0.360 |
| 1.00 | 0.297* | 0.318* |
| 1.25 | 0.470 | 0.480 |
| 1.50 | 0.470* | 0.477* |

Table 27. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 4B (FRP Wrap After 6 Months of Exposure)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.330* | 0.318* |
| 0.50 | 0.364* | 0.364* |
| 0.75 | 0.285 | 0.290 |
| 1.00 | 0.118 | 0.123 |
| 1.25 | 0.115 | 0.120 |
| 1.50 | 0.105 | 0.109 |

Table 28. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 5A (Polymer Resin Coating Since Day 1)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.069* | 0.078* |
| 0.50 | 0.076 | 0.076 |
| 0.75 | 0.060 | 0.060 |
| 1.00 | 0.053 | 0.061 |
| 1.25 | 0.072 | 0.073 |
| 1.50 | 0.076 | 0.076 |

Table 29. Final Acid-Soluble Chloride Content of Prestressed Concrete Beam End 5B (FRP Wrap Since Day 1)

| Average Depth (inches) | Chloride Content, 5 minute Test (% by weight of concrete) | Chloride Content, 24 Hour Test (% by weight of concrete) |
|---|---|---|
| 0.25 | 0.064 | 0.068 |
| 0.50 | 0.054 | 0.058 |
| 0.75 | 0.056 | 0.062 |
| 1.00 | 0.062 | 0.070 |
| 1.25 | 0.064* | 0.068* |
| 1.50 | 0.118* | 0.118* |

Table 30 shows the above chloride data in a slightly different form. The 24-hr chloride test data shown above are summarized by focusing on 0.75 inch and 1.50 inch measurements. The chloride levels at each of the two levels are given a numerical rating of 1 to 8. If the chloride content is between zero and 0.1%, then a rating of 1 is given, etc. For example, a chloride content of .35 would be given a numerical rating of 4. Chloride contents higher than 0.7% are given a rating of 8. As will be seen in the following sections of this report, other comparative performance measures (for cracking and corrosion) are also based on a numerical measure from 1 to 8. It is clear that that among beam-ends that were pretreated from the first day, the polymer resin coating and the Silane sealer were the most effective. The FRP wrap was very close behind. Among the beam-ends that were treated after 6 months of exposure, the Silane sealer and the epoxy coatings had the least chloride contents. The highest chloride contents were observed in the patched beam-end 2B.

Table 30. Comparative Chloride Content Ratings* for All Beam-Ends Based on 24-hr Data at 0.75 and 1.5 in. Depths

| Beam-End | Rating at 0.75 in. | Rating at 1.5 in. | Ave. Rating |
|---|---|---|---|
| 1A | 1 | 1 | 1 |
| 1B | 3 | 2 | 2.5 |
| 2A | 3 | 1 | 2 |
| 2B | 8 | 8 | 8 |
| 3A | 1 | 1 | 1 |
| 3B | 2 | 2 | 2 |
| 4A | 4 | 5 | 4.5 |
| 4B | 3 | 2 | 2.5 |
| 5A | 1 | 1 | 1 |
| 5B | 1 | 2 | 1.5 |

Ratings based on numerical rating from 1 to 8 (1 best, 8 worst)
Shaded rows correspond to beam-ends that were treated after 6 months of exposure.

### 5.1.3 Corrosion Current

A regulated voltage of 9V was applied continuously over the course of the exposure cycles to facilitate an accelerated corrosion process and speeding the intrusion of chlorides. Plots of the corresponding corrosion current versus time (for the data collected in the first 10 months of exposure) are illustrated in Figures 28-32. The completions of the first exposure cycles are indicated on the plots. The prefixes (pre, post) denote whether the treatment was applied before the start of the accelerated corrosion regime, or if they were applied after experiencing 6 months of exposure. These figures show periodic increases (spikes) in the corrosion currents. These are associated with temporary stoppages of voltage applications. The short-term increase in currents after restoration of voltage is also observed in tests done by Lee [30].

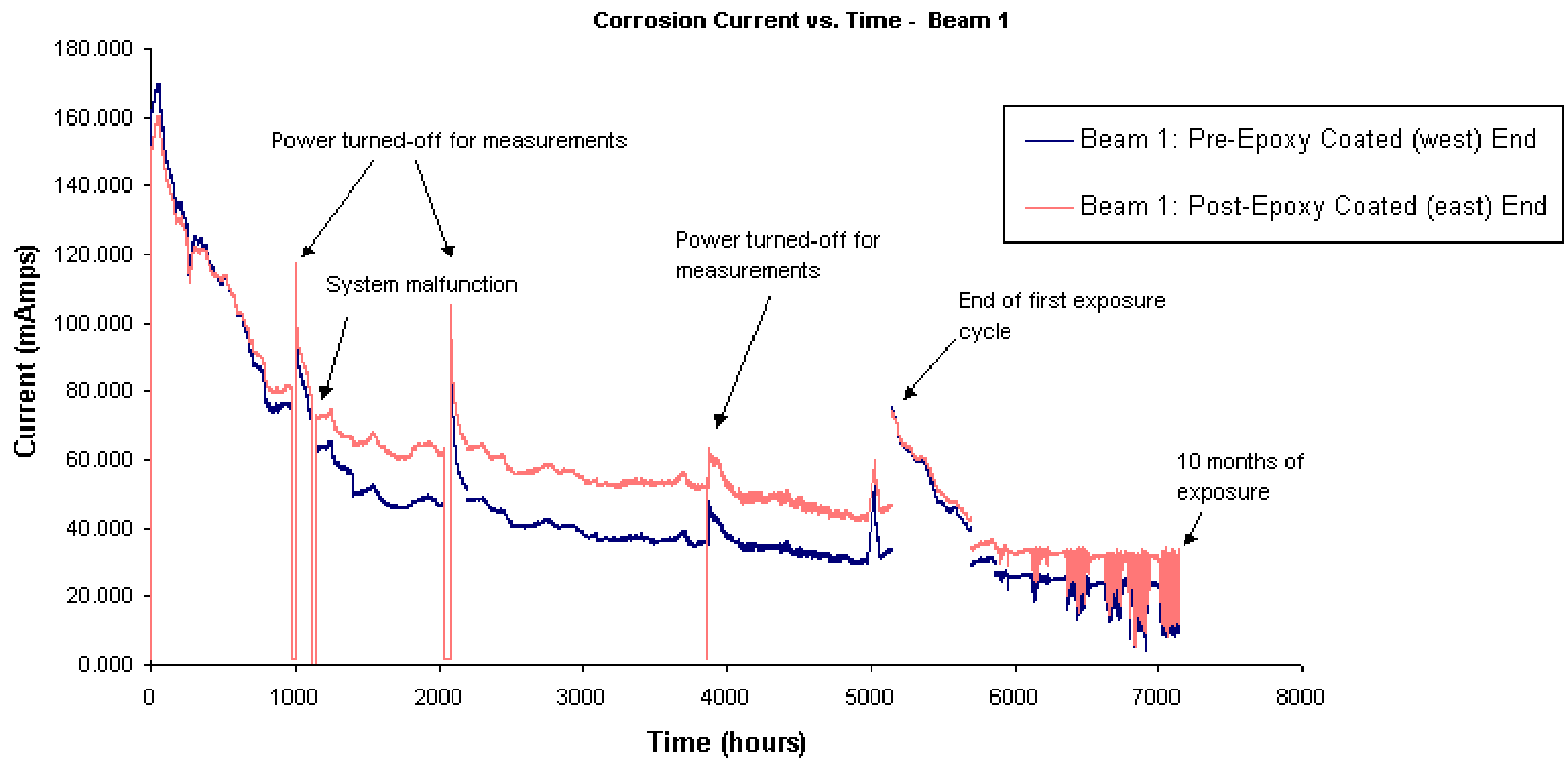



Figure 28. Corrosion Current vs. Time – Beam-Ends 1A (West) and 1B (East)

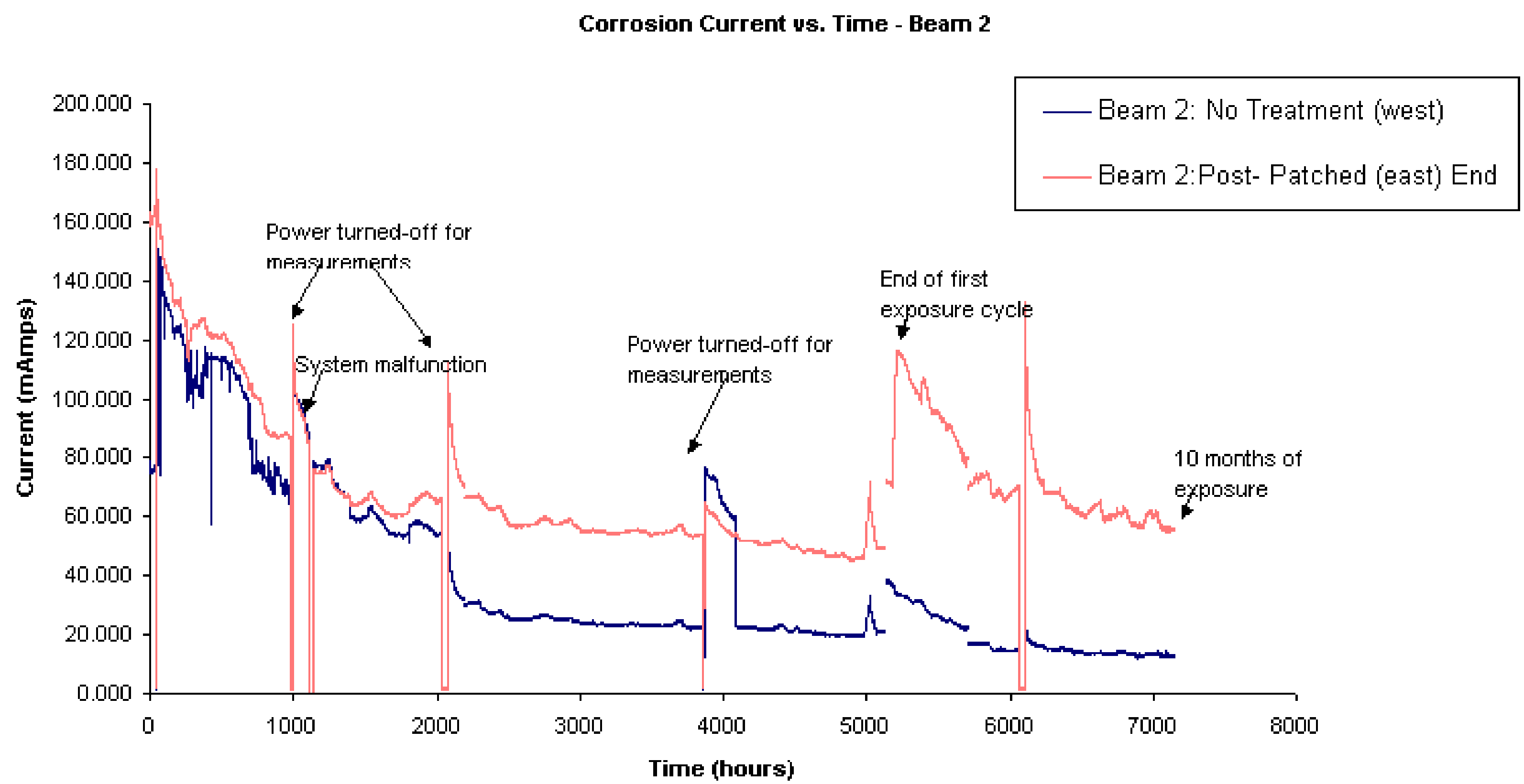



Figure 29. Corrosion Current vs. Time – Beam-Ends 2A (West) and 2B (East)

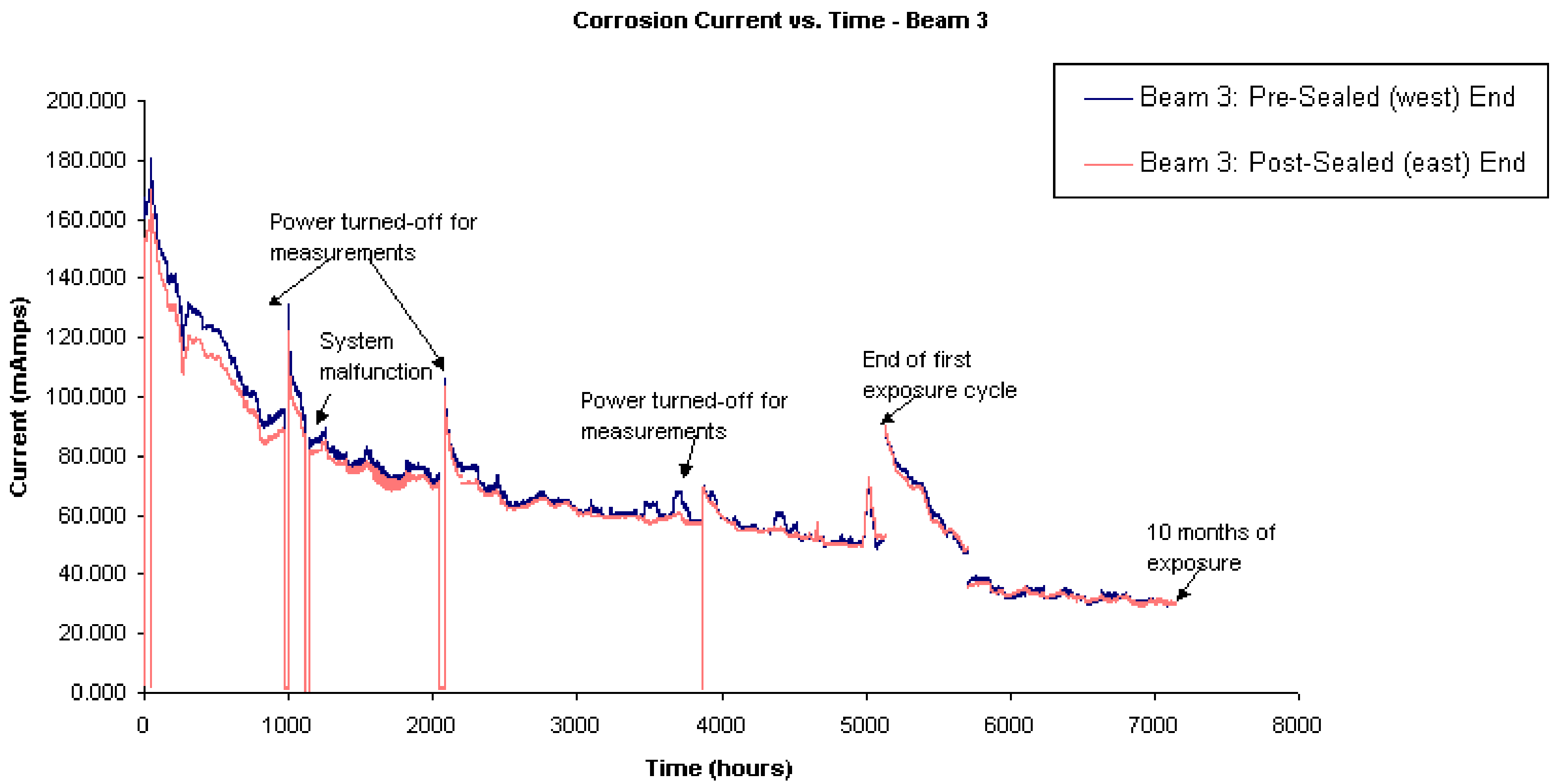



Figure 30. Corrosion Current vs. Time – Beam-Ends 3A (West) and 3B (East)

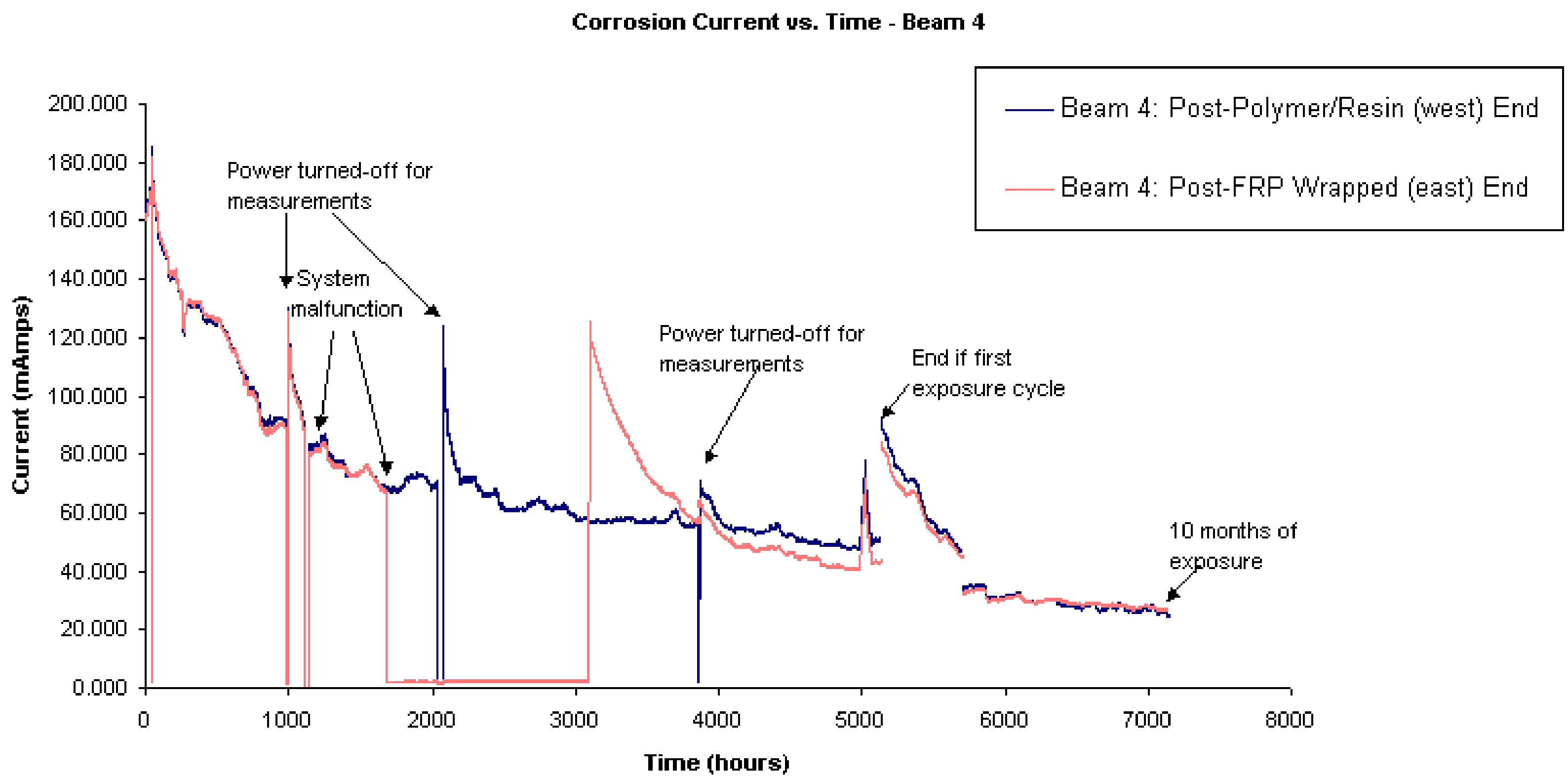



Figure 31. Corrosion Current vs. Time – Beam-Ends 4A (West) and 4B (East)

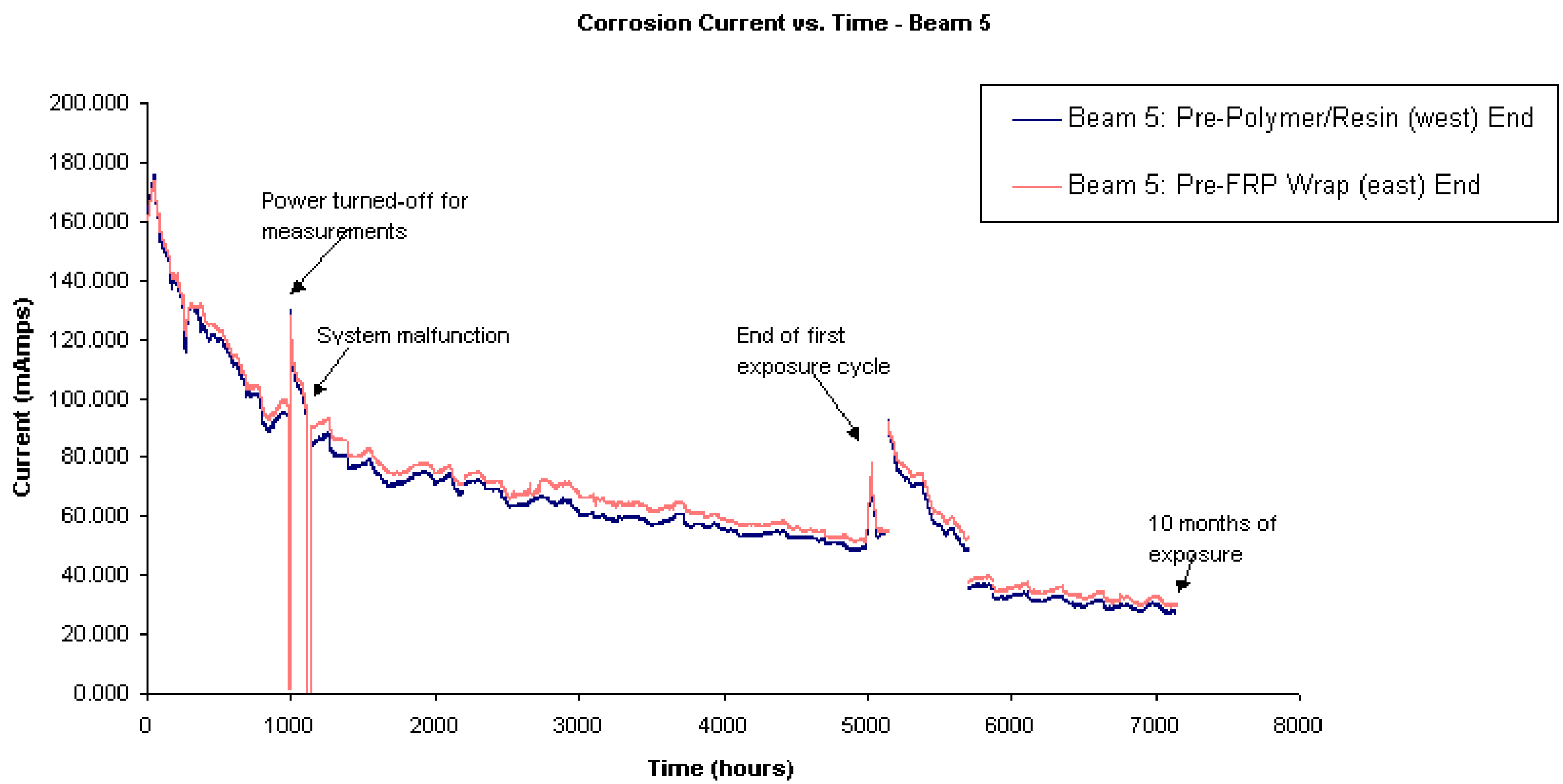



Figure 32. Corrosion Current vs. Time – Beam-Ends 5A (West) and 5B (East)

All curves exhibit a decrease in current over the 10 months of the experiment reported here. This reduction is commonly observed in such experiments, and is due in part to the fact that corrosion products increase the resistance at the surface of strands. Because of the exponential nature of the curve, the results obtained subsequent to the first 10 months of exposure are not plotted. The curves for the two ends of beam 1 are approximately similar until about the 800-hour mark, after which the curves begin to diverge. The pre-coated beam end (epoxy coated from Day 1) demonstrates a larger decrease in current at approximately 1500 hours in comparison to the untreated end. The cumulative area under the corrosion current versus time graph is indicative of the amount of steel loss due to corrosion. Since the pre-coated end has a smaller cumulative area under its curve, it can be deduced that this end is experiencing less steel loss over time. Therefore, the beam end treated with epoxy coating since Day 1 is experiencing less steel corrosion in comparison to the untreated (later coated) end.

The corrosion vs. time curves for the two ends of beam 2 are relatively similar until about 2000 hours into the experiment. After which, the "no-treatment" or west end experiences a significant decrease in current. Since these ends were exposed to the same exposure condition and both were initially untreated, their curves should be approximately equal for the first 6 months of the study. Given that the untreated end diverges so significantly, it can be deduced that there may have been electrical connection problems occurring with this end. It was observed that at the end of the first phase of exposure, there was only one undamaged connection between the beam end and the applied voltage. Therefore, the difference observed between the curves for the ends of beam 2 is more than likely due to electrical connection problems, and does not reflect that less corrosion is occurring in the untreated, west end compared to the untreated, east end.

The corrosion current versus time curves for the two ends of beam 3 are generally similar for both the pre-sealed (west) end and the untreated, later sealed (east) end. This behavior is observed at the end of the first phase of the experiment and continues after 10 months of exposure. Since these curves are exhibiting similar behavior, it can be concluded that the pre-sealed end behaved the same as the initially untreated end. Therefore, this data seems to indicate that the penetrating sealer did not have a noticeable effect on preventing corrosion and the subsequent steel loss in the beam.

The corrosion current versus time curves for the two ends of beam 4 are nearly the same for both initially untreated ends. The exception is between approximately 1700 and 3000 hours, where the current drops to zero for the post-FRP wrapped (east) end. The drop in current was due to a loose connection between that end and the applied voltage. When the drop in current was observed, the connection was evaluated and remedied. After the readings stabilized once the connection was reestablished, the behavior of both curves returned to be nearly equal. Since both ends were initially untreated and subjected to the same exposure conditions, the graphs should display nearly the same behavior. For the 10 months of total collected data, the curves continue to be approximately equal after the polymer (resin) and FRP wrap was applied.

The corrosion current versus time curves for the two ends of beam 5 are nearly the same for the 10 months of collected data. The end pretreated with the polymer (resin) has a slightly less corrosion current in comparison to the end pretreated with FRP wrap (east). Form the existing data collected, it can be concluded that both ends are experiencing similar corrosion damage, and therefore have similar effectiveness.

### 5.1.4 Effect of Time on Corrosion Rates in Field Structures

Vu and Stewart [49] developed a relationship between time since corrosion initiation and corrosion rate. The author states that corrosion rates predicted by his model appear to be reasonable and within the range of typical corrosion rates found in literature and therefore the model error is not expected to be high. However, the model is subjected to limitations since it has been validated with minimal experimental data, and the data that was collected was over a short period of time. A graphical representation of their model is illustrated in Figure 33. The vertical axis refers to the ratio of corrosion current at any particular time to the initial corrosion current. This representation is generally similar in shape to the experimental data observed.

The time it takes for the corrosion current to be reduced by 50% is approximately 8 years, or 70,080 hours. On average, the corrosion current data collected from this experiment shows the time it takes for the corrosion current to be reduced 50% is approximately 1250 hours, or 0.14 years. In other words, the accelerated corrosion regime compressed the time to initiate corrosion. If it is assumed that the relationship is similar in both cases (which may not be a sound assumption), then an estimate of the amount of time compression can be made. In this case, it could be estimated that 10 months of exposure in the laboratory has simulated 40 years in the field. However, the measured response after power shutdowns indicates that the rate of reduction can be artificially high in some cases. Therefore, the time compression ratio cannot be conclusively established based on available data.

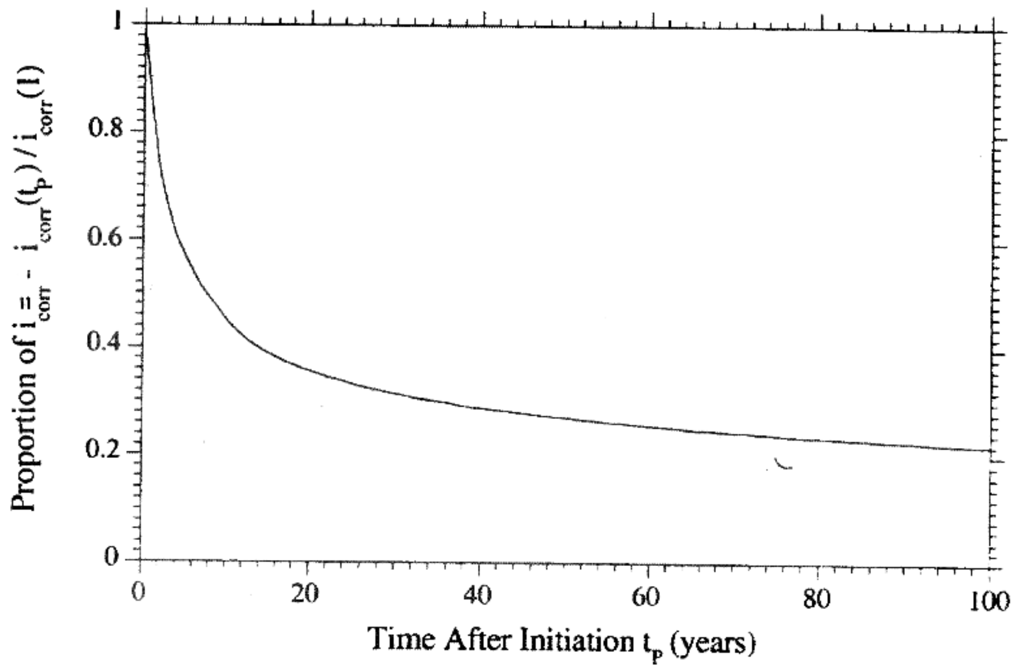



Figure 33. Effect of Time on Corrosion Rate

### 5.1.5 Best Fit Curves

Best-fit curves were developed to remove the unrelated "noise" of the system (Figures 34-38) using the first 6 months of data. All irregular data was deleted for the best-fit curve calculations. The uncharacteristic data resulted from power surges in the system or when the system was shut down to obtain half-cell readings. To determine the best-fit curve, it was assumed that the response curve was essentially exponential. Therefore, the natural log of the current was first calculated. The slope, y-intercept, and coefficient of correlation of the natural log of the corrosion current versus time were determined. The following equation was employed to derive the best-fit curve for each beam end:

$$y = ae^{-bt} \quad \text{[Eq. 5.1.5-1]}$$

Where, a is the exponent of the y-intercept (mAmps), b is the slope, and t is the time (hours). The coefficient of correlation was calculated for each curve. The coefficient of correlation expresses the strength of the linear relationship between the two variables. Hence a value of 1 indicates that the t and ln(y) are perfectly correlated. All curves possess a coefficient of correlation of 90% or greater. Therefore, it can be concluded that a linear relationship exists between the natural log of corrosion current and time, and the assumption of exponential curve is generally valid.

All curves demonstrated a decrease in corrosion current over time. As stated earlier, the pre-coated (west) end of beam 1 had a smaller corrosion current in comparison to the initially untreated end. The untreated (west) end of beam 2 also demonstrates a much smaller corrosion current that the other initially untreated (east) end of beam 2. Again, this is likely due to issues encountered with the electrical system, and is not representative of the actual corrosion damage occurring. The initially sealed (west) end of beam 3 had slightly less corrosion current at the start of the experiment, but the currents began to converge with the initially untreated (east) end of beam 3 at the end of the first phase of the exposure. This seems to indicate that over 6-month exposure to an accelerated corrosion regime, the pre-sealed end has slightly better effectiveness as applying no pretreatment.

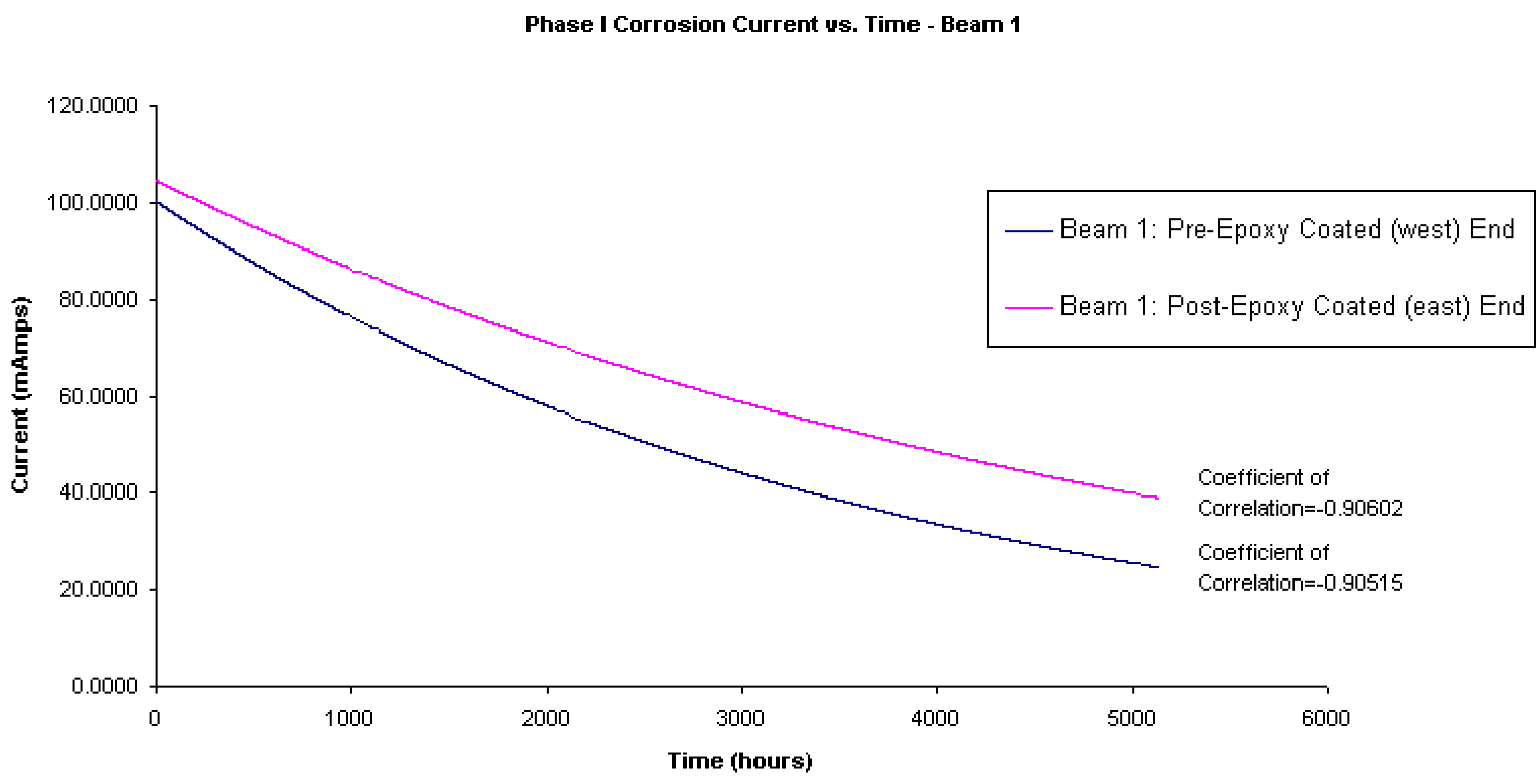



Figure 34. Best-Fit Curve: Corrosion Current vs. Time – Beam 1

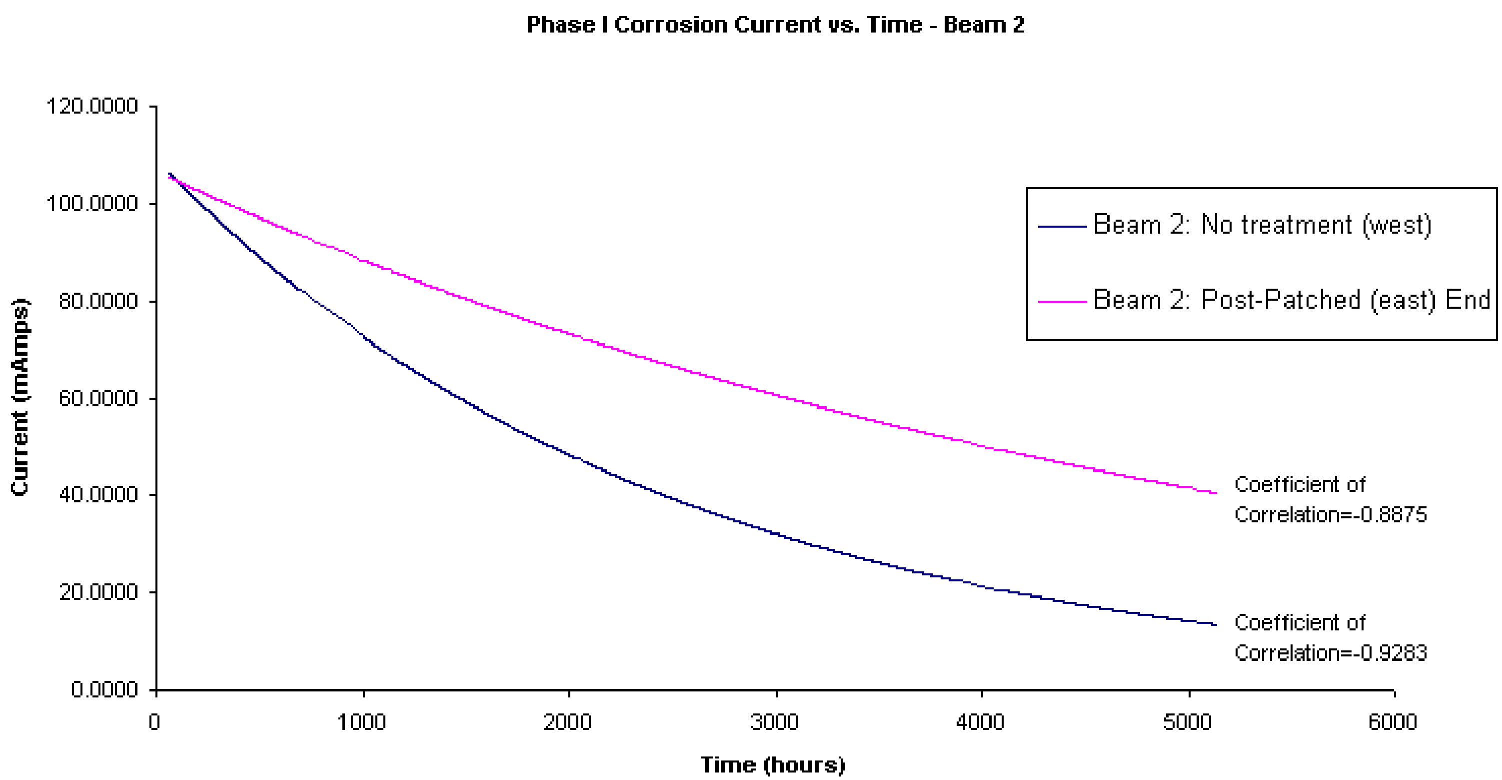



Figure 35. Best-Fit Curve: Corrosion Current vs. Time – Beam 2

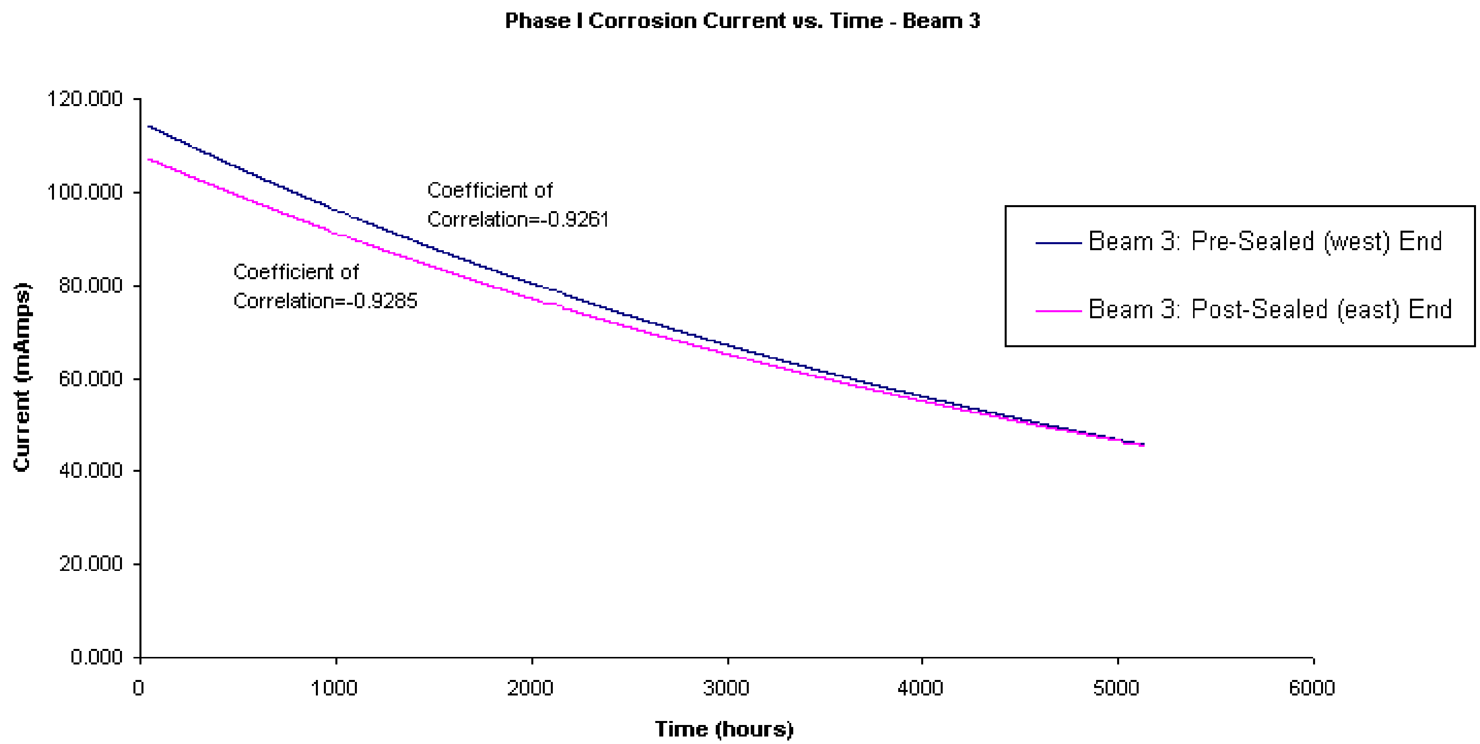



Figure .36. Best-Fit Curve: Corrosion Current vs. Time – Beam 3

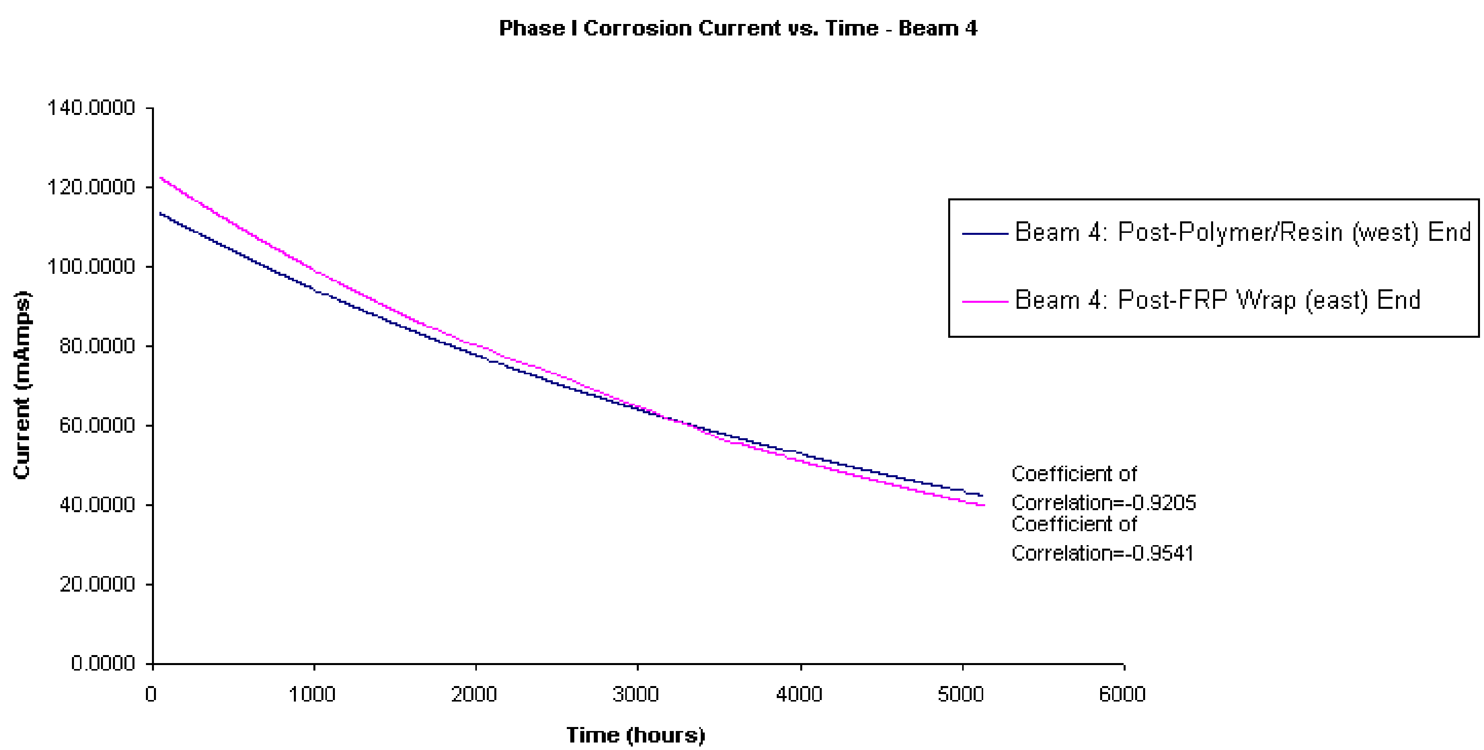



Figure 37. Best-Fit Curve: Corrosion Current vs. Time – Beam 4

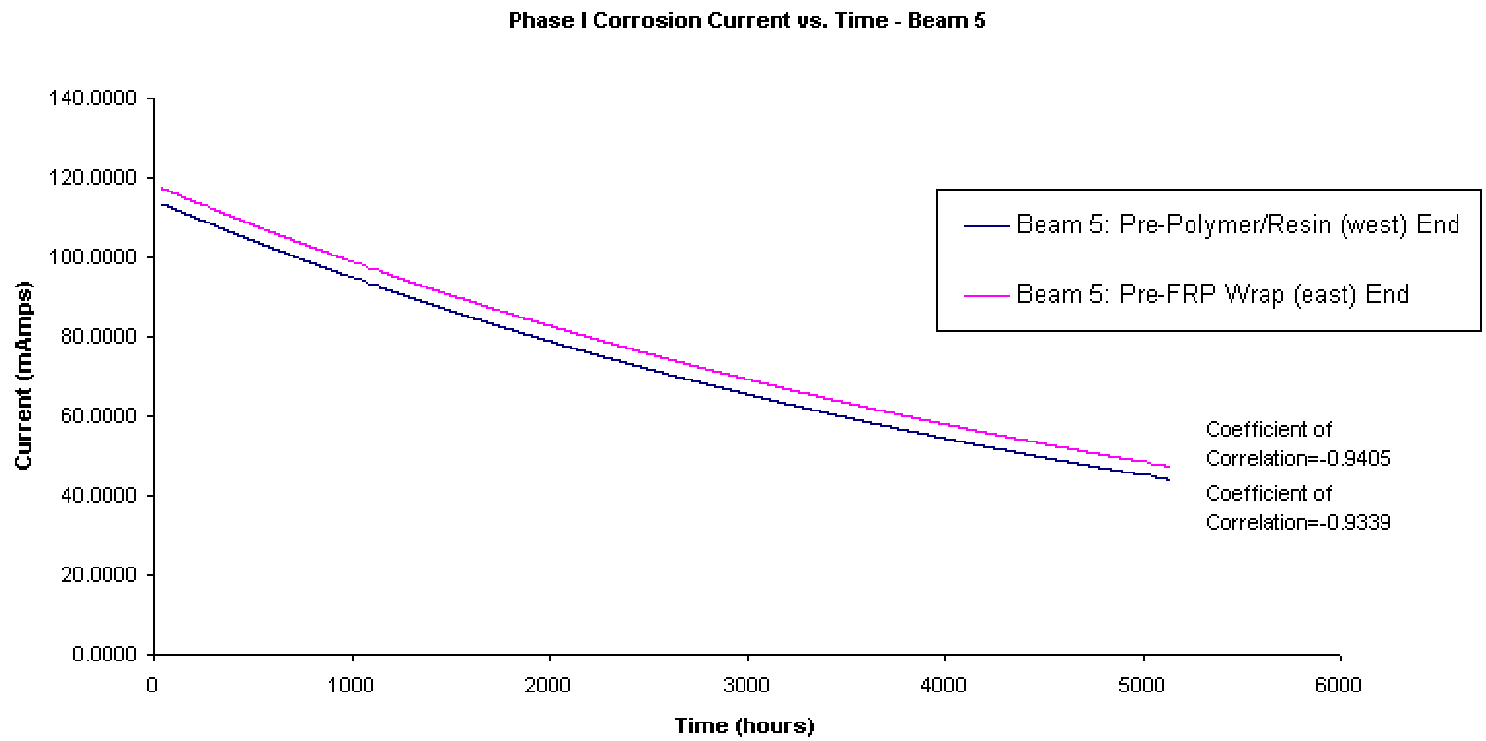



Figure 38. Best-Fit Curve: Corrosion Current vs. Time – Beam 5

Both initially untreated ends of beam 4 have nearly the same behavior for the first 6 months, which correlated with the fact that both ends were exposed to the same conditions. Both curves for beam 5 are decreasing at a very similar rate. The end pretreated with the polymer (resin) has a slightly less corrosion current in comparison to the end pretreated with the FRP wrap. Since the data for beam 5 are so similar, it can be deduced that both treatments have similar effectiveness at that time.

Figure 39 illustrates the combination of corrosion current versus time for all the beam-ends. The "no treatment" end of beam 2 exhibits the lowest corrosion current over time. As explained earlier, this is likely due to electrical connection problems with this particular end, and is not representative of its true behavior in preventing corrosion. The next lowest curve is the end of beam 1 pretreated with a coating. The end that exhibits the largest corrosion current versus time is the end pretreated with the FRP wrap. However, all curves for each of the beam-ends are clustered closely together. Therefore, based on the 6-month exposure data, a conclusive assessment of the effectiveness of various treatments cannot be made.

**5.1.6 Steel Loss**

Steel loss was estimated from the corrosion currents using the following equation:

$$w_t = \frac{At_m}{zF}\int I(t)dt \qquad \text{[Eq. 5.1.6-1]}$$

where $At_m$ is the atomic mass of the metal, z is its valency, F is Faraday's constant (96487 C/mol), dt the time frame, and I(t) is the best-fit curve extrapolated from the current

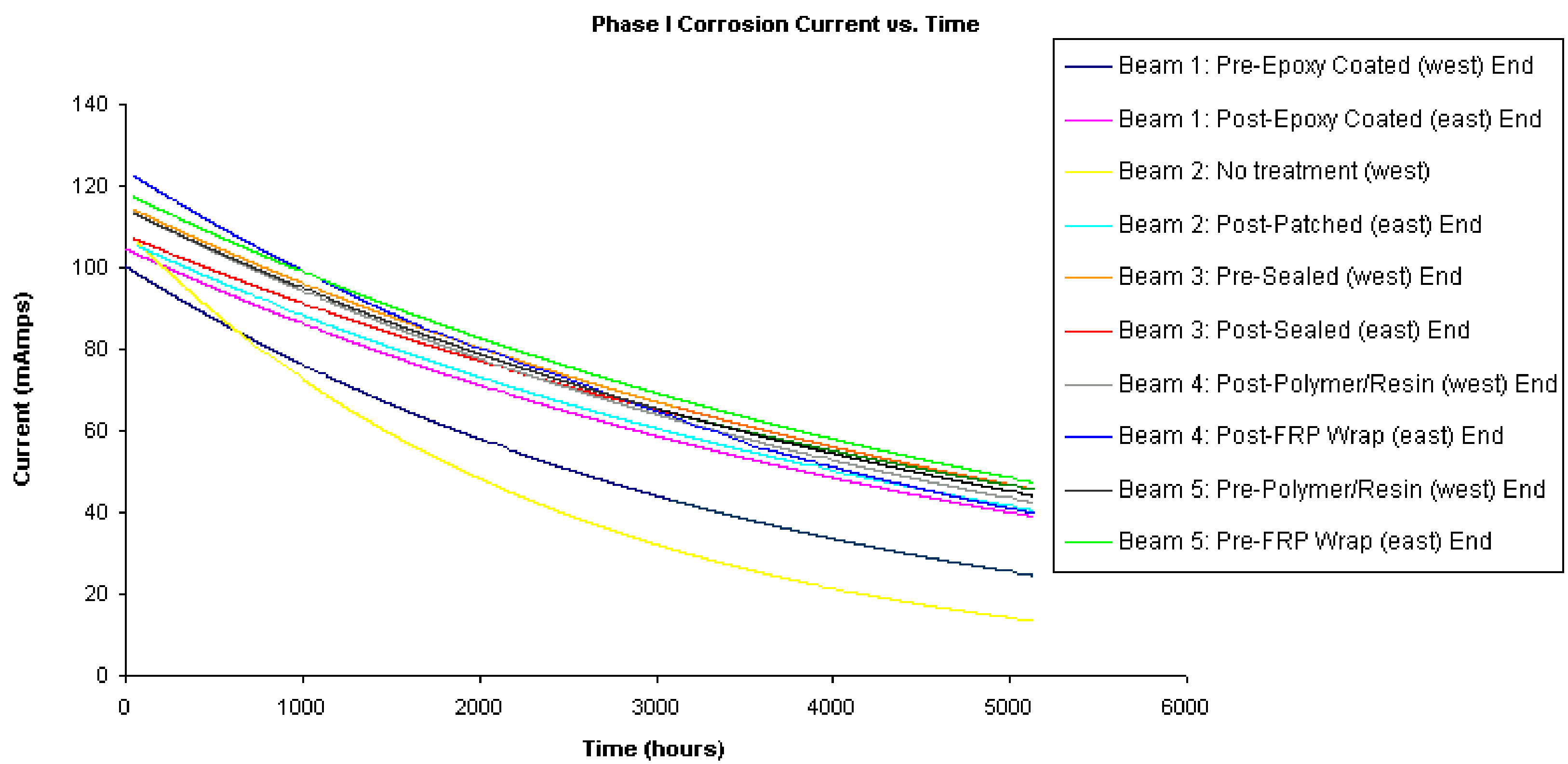



Figure 39. Best-Fit Curve: Corrosion Current vs. Time – All Beam Ends

measured. For reinforcing steel, which is primarily iron, the atomic mass is 55.85 g/mol and the valency is 2. Table 31 lists the calculated steel loss for each beam end (see Appendix E for calculations).

Table 31. Steel Loss

| Beam End | Steel Loss | % Steel Loss** |
|---|---|---|
| Beam 1: pre-coated | 288 | 1.7 |
| Beam 1: untreated (post-coated) | 356 | 2.1 |
| Beam 2: untreated | 245* | 1.4* |
| Beam 2: untreated (patched) | 366 | 2.1 |
| Beam 3: pre-sealed | 402 | 2.3 |
| Beam 3: untreated (post-sealed) | 387 | 2.2 |
| Beam 4: untreated (post-polymer) | 388 | 2.3 |
| Beam 4: untreated (post-FRP) | 396 | 2.3 |
| Beam 5: pre-polymer | 394 | 2.3 |
| Beam 5: pre-FRP | 415 | 2.4 |

*Possibly affected by electrical problem.
**Based on strand mass only (assuming corrosion takes place on strands only). These percentages could be reduced by applying a factor of 0.166 if the mass of the stirrups is considered.

The steel loss determined from the prior equation is calculated for the entire steel cage of the beam. The steel loss of interest is localized in the beam end regions and cannot be isolated from the loss over the entire reinforcing cage. Due to electrical problems, the value calculated for the untreated end of beam 2 is believed not to be accurate. It can be concluded that the pre-coated beam end (epoxy coated from Day 1) has experienced the least steel loss in comparison to the other ends. Also, the end pretreated with the FRP system polymer has experienced the highest steel loss. Not including the data from the "no treatment" end of beam 2, the average steel loss was 377 grams with a standard deviation of 38 grams. Since, the range of values is small, it cannot be conclusively determined which treatment provided the most effective corrosion protection from this method of analysis.

### 5.1.7 Half-Cell Potential Data

Half-cell measurements using a copper-copper sulfate electrode were obtained for each beam end. Half-cell measurements were taken approximately every month for the first exposure cycle. A contour plot of the half-cell readings at the beginning and end of the first exposure cycle as well as after 10 months of exposure are shown in Figures 42-58. As stated earlier, half-cell readings were not obtained for the treated beam-ends because of lack of electrical coupling in treated beams. The complete data and contour graphs are located in Appendix F.

Initial half-cell potentials were relatively uniform at all points measured. Whereas the half-cell readings after the first exposure cycle vary depending on their location on the beam. The values increase substantially as measurements neared the end of the beam. The highest readings were located on the bottom flange near the edge of the beam. These readings are consistent with the flow of the salt water down the end of the beam. The water normally traveled down the front face of the beam, curved around the bottom flange and then was collected in the trough system. Hence, the corrosion should be occurring in a similar location as the path of the salt water.

According to Emmons [15], it is generally agreed that the half-cell potential measurements can be interpreted as follows:

- Less negative than –0.20 volts indicates a 90% probability of no corrosion.
- Between –0.20 and –0.350 volts, corrosion activity is uncertain.

- More negative than –0.35 volts is indicative of a greater than 90% certainty that corrosion is occurring.

Since the polarity of the experimental setup is reversed from the standard method, the values obtained are in the positive range. According to Emmons [15] interpretation, after 6 months of exposure to a corrosive environment, the half-cell readings for the end of beam 1 indicate that corrosion is not occurring. The half-cell readings (at 6 months) for the ends of beam 2 and 4 indicate that it is inconclusive whether or not corrosion is occurring. However, the east end of Beam 3 has some half-cell readings on the bottom flange outer corner that indicate corrosion is occurring at these regions. The half-cell potential readings for beam ends 2A (no treatment) and 2B (patched) after 18 months of exposure clearly show corrosion activity in the beam-ends. Comparisons of Figure 45 with Figures 47 and 51, and Figure 46 with Figures 48 and 52 clearly show the progression of corrosion activities.

Half-cell potential readings were no longer taken on the surfaces treated after the first 6 months of exposure. The measurements were only taken on the non-treated beam-ends since surface treatments provide a non-conductive barrier that renders the half-cell measurements ineffective. The ends of beam 2 were the only remaining beam-ends that did not receive a surface treatment. After 10 months of exposure, the patched (east) end yields a higher potential in comparison to the untreated end. This trend is also observed at the end of 18 months. Figure 52 (patched end) shows a much larger area with half-cell potential readings of over 400 compared to Figure 51 (untreated end).

Figures 40 and 41 illustrate the orientation of the half-cell contour graphs on the prestressed beams, if directly facing the beam.

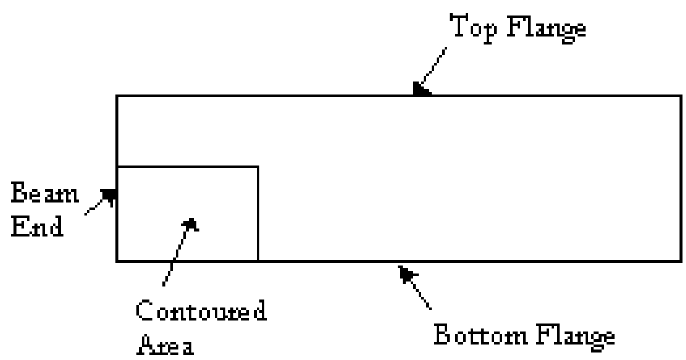



Figure 40. Southeast or Northwest Contour Orientation

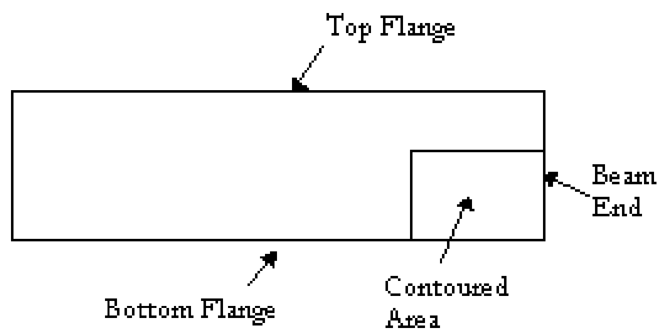



Figure 41. Southwest or Northeast Contour Orientation

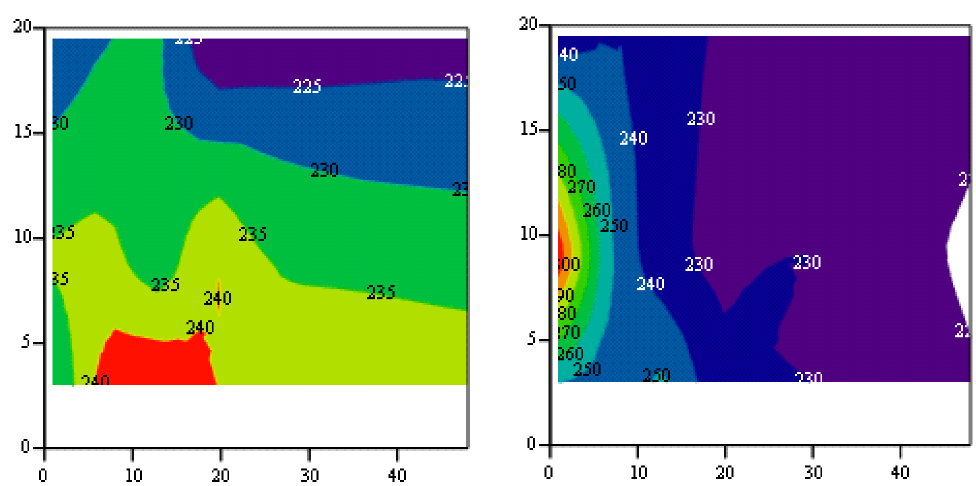


Figure 42. Initial Half-Cell Readings Beam 1B – Southeast End (left), Northeast End (right)

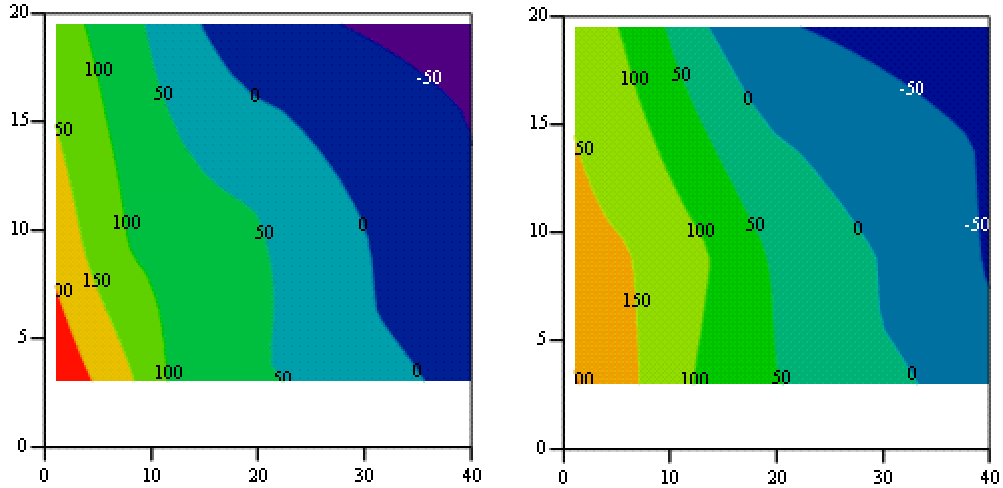



Figure 43. Half-Cell Readings Beam 1B(after 6 months) – Southeast End (left), Northeast End (right)

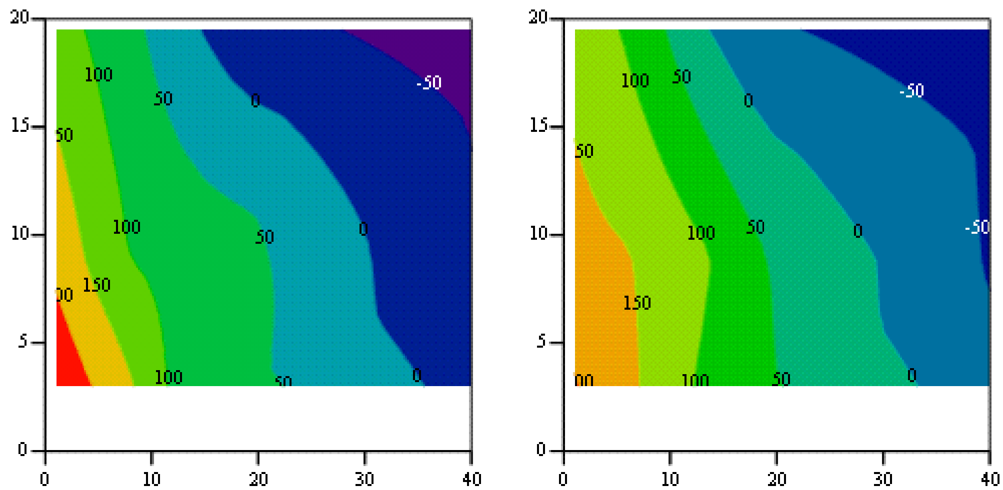



Figure 44. Half-Cell Readings Beam 1B(after 10 months) – Southeast End (left), Northeast End (right)

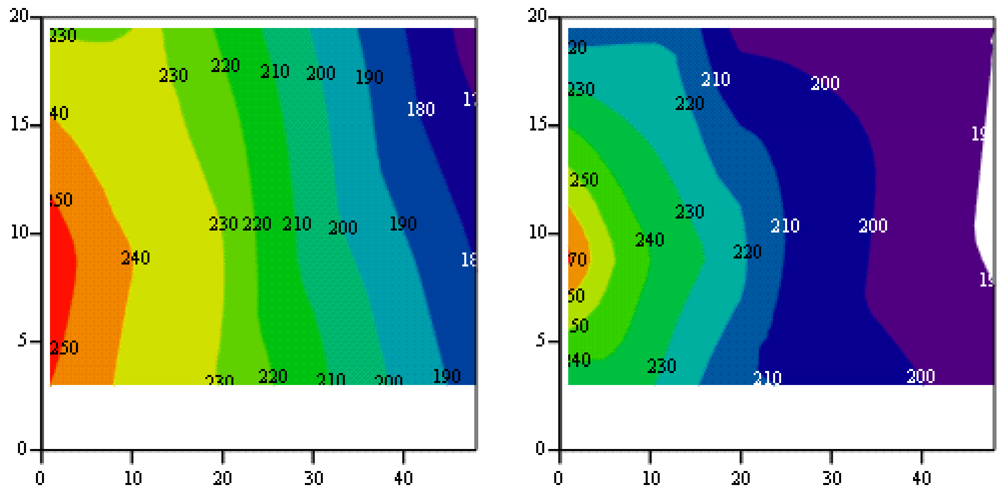



Figure 45. Initial Half-Cell Readings Beam 2A – Southwest End (left), Northwest End (right)

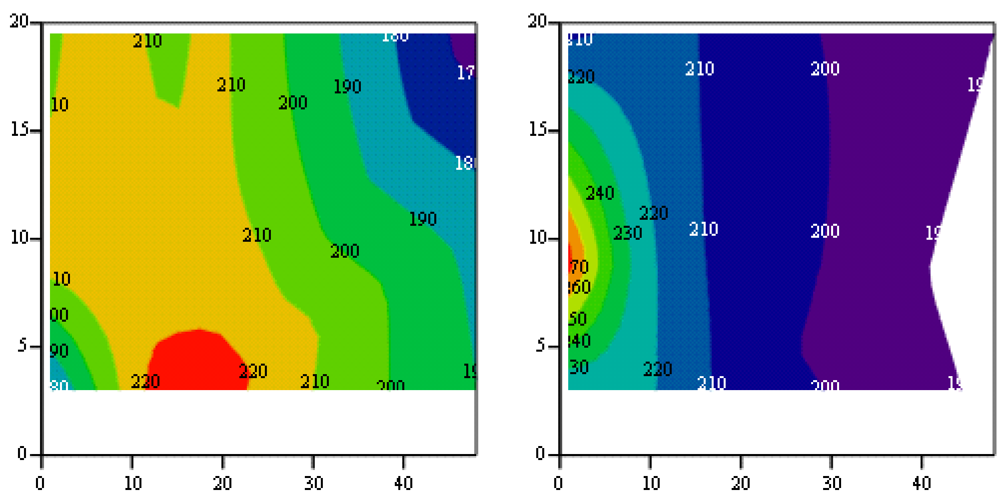



Figure 46. Initial Half-Cell Readings Beam 2B – Southeast End (left), Northeast End (right)

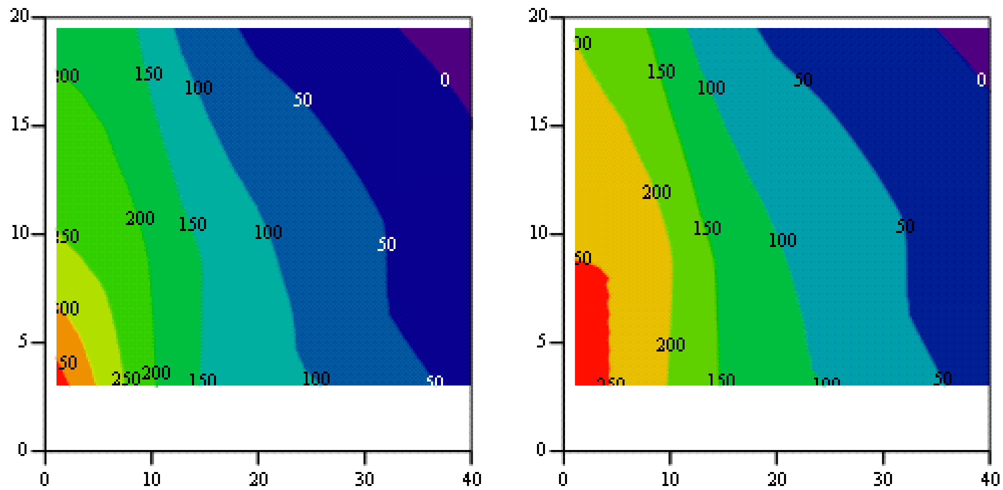



Figure 47. Half-Cell Readings Beam 2A(after 6 months) – Southwest End (left), Northwest End (right)

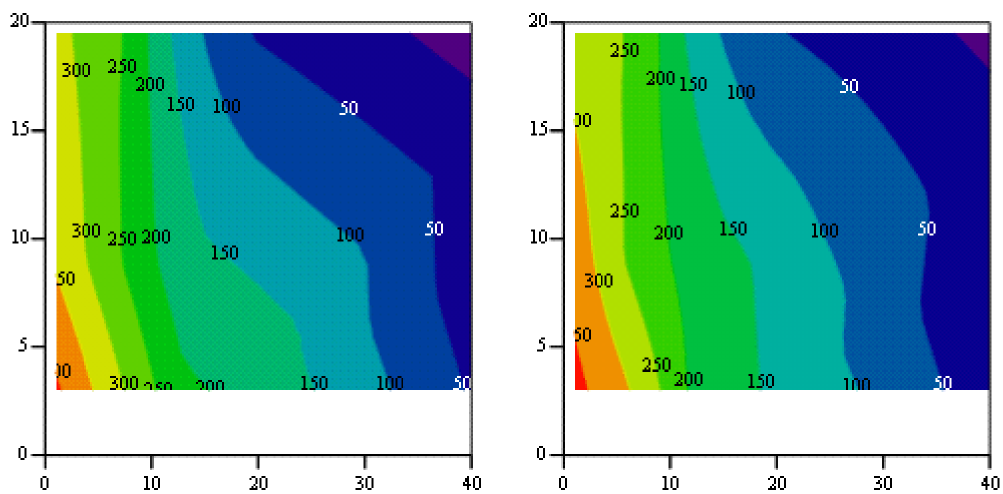



Figure 48. Half-Cell Readings Beam 2B(after 6 months) – Southeast End (left), Northeast End (right)

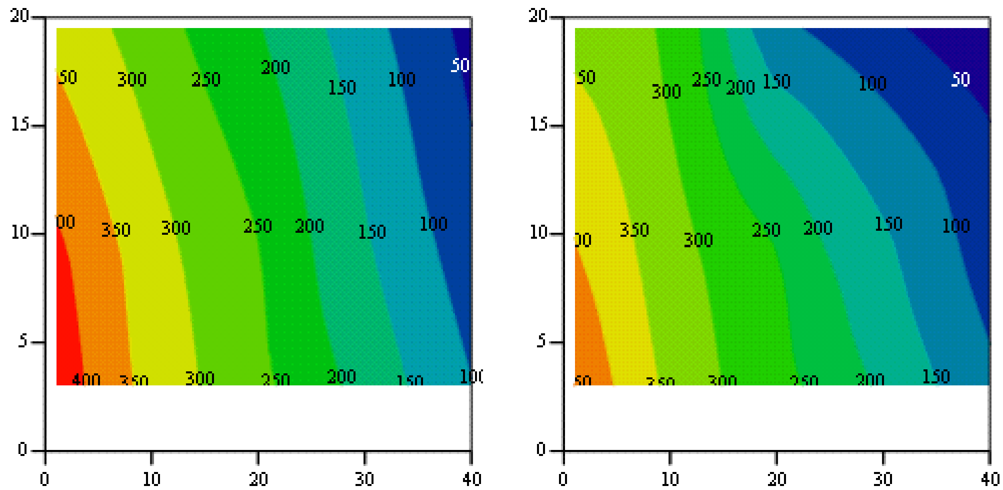



Figure 49. Half-Cell Readings Beam 2A(after 10 months) – Southwest End (left), Northwest End (right)

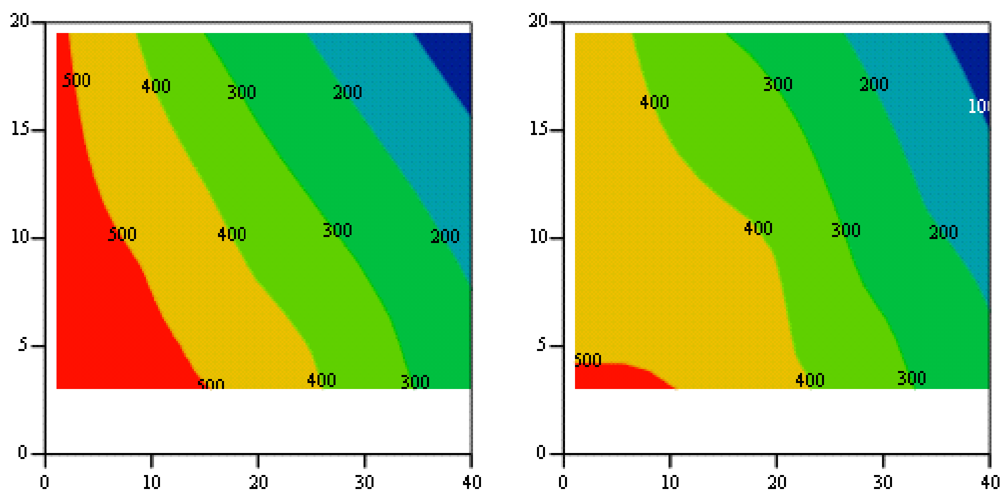



Figure 50. Half-Cell Readings Beam 2B(after 10 months) – Southeast End (left), Northeast End (right)

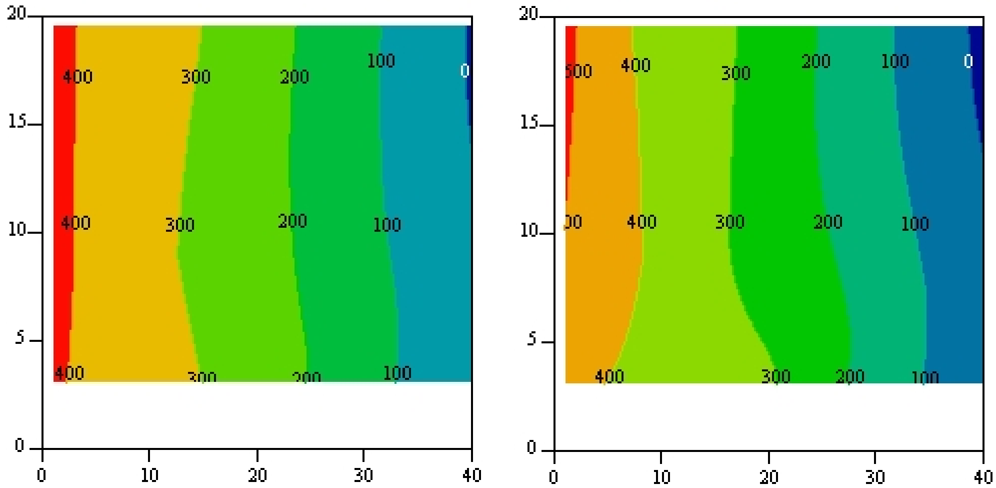



Figure 51. Half-Cell Readings Beam 2A(after 18 months) – Southwest End (left), Northwest End (right)

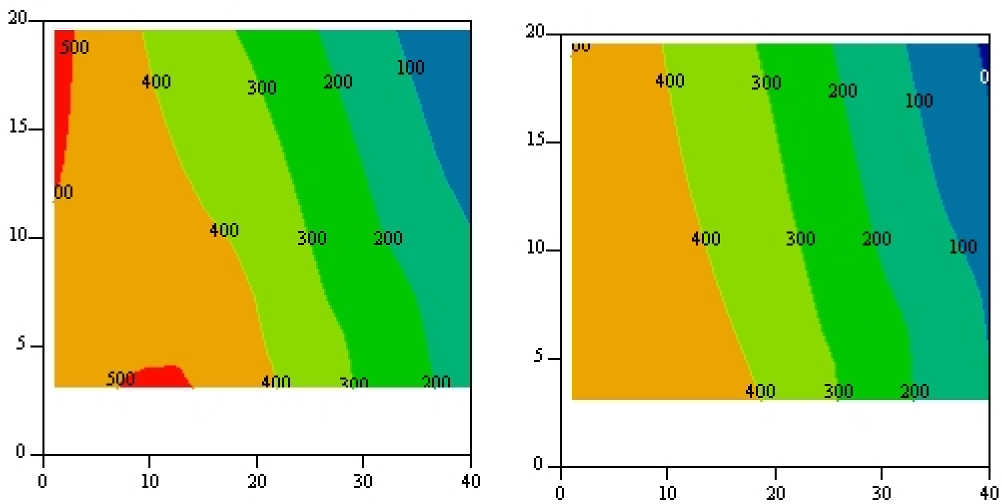



Figure 52. Half-Cell Readings Beam 2B(after 18 months) – Southeast End (left), Northeast End (right)

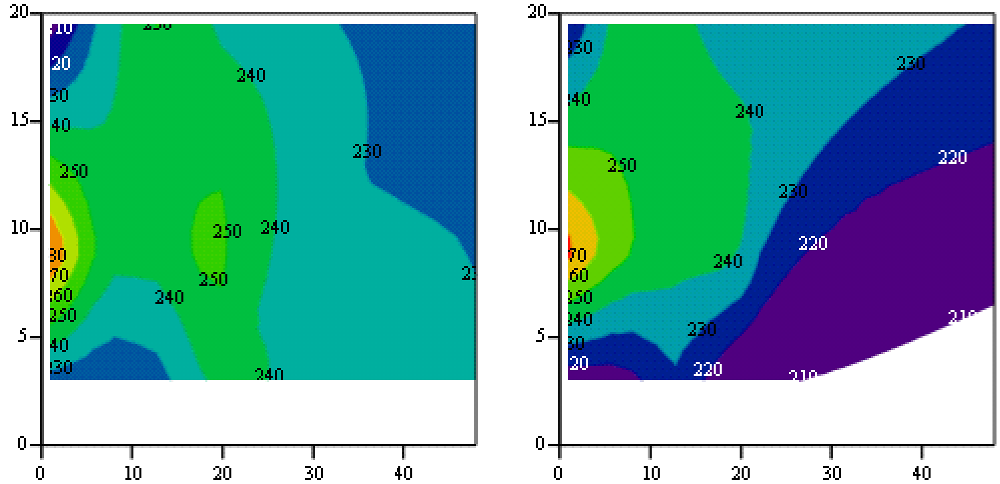



Figure 53. Initial Half-Cell Readings Beam 3B – Southeast End (left), Northeast End (right)

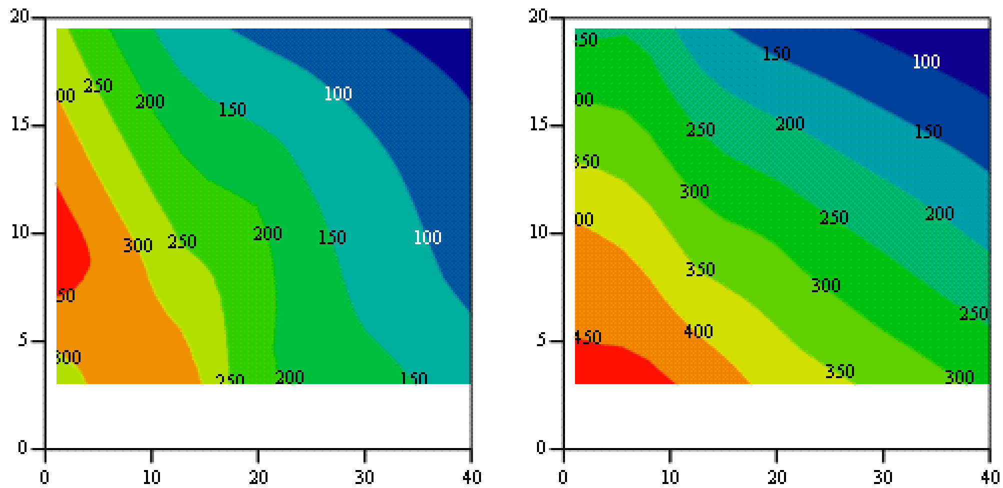



Figure 54. Half-Cell Readings Beam 3B(after 6 months) – Southeast End (left), Northeast End (right)

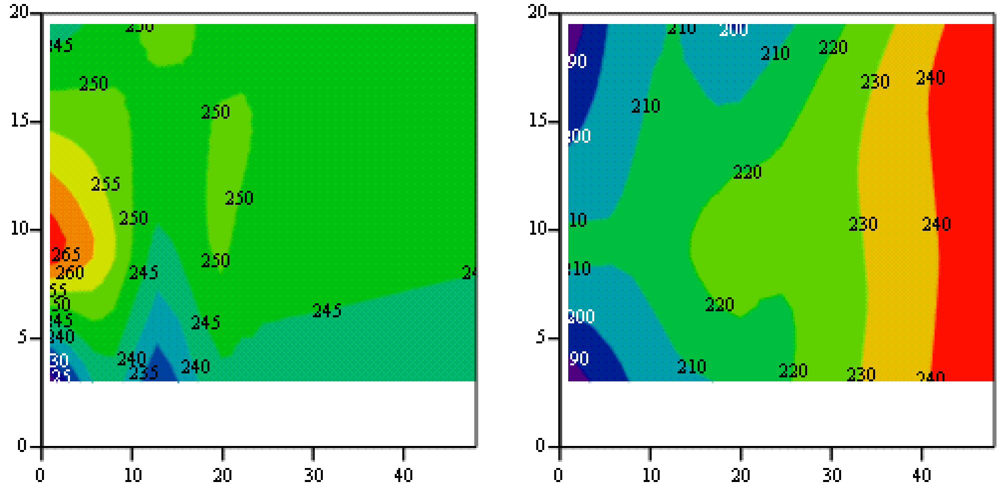



Figure 55. Initial Half-Cell Readings Beam 4A – Southwest End (left), Northwest End (right)

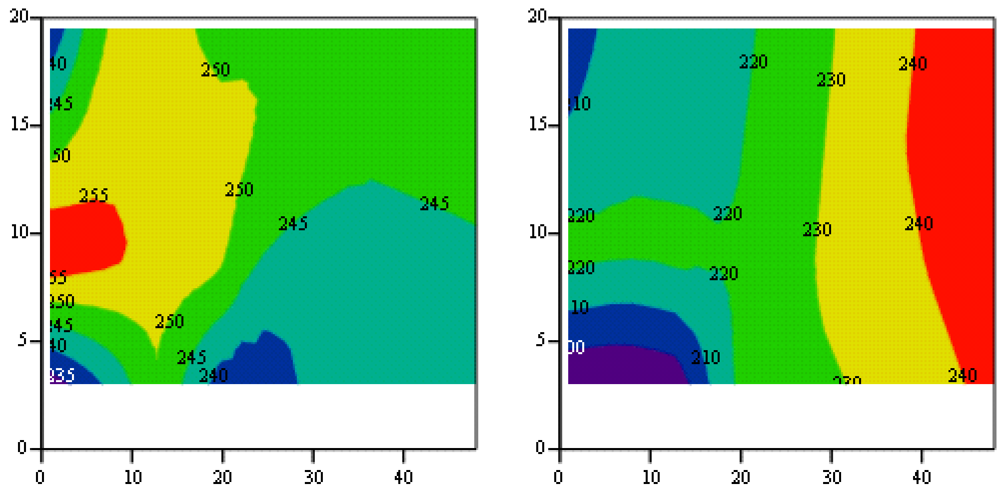



Figure 56. Initial Half-Cell Readings Beam 4B – Southeast End (left), Northeast End (right)

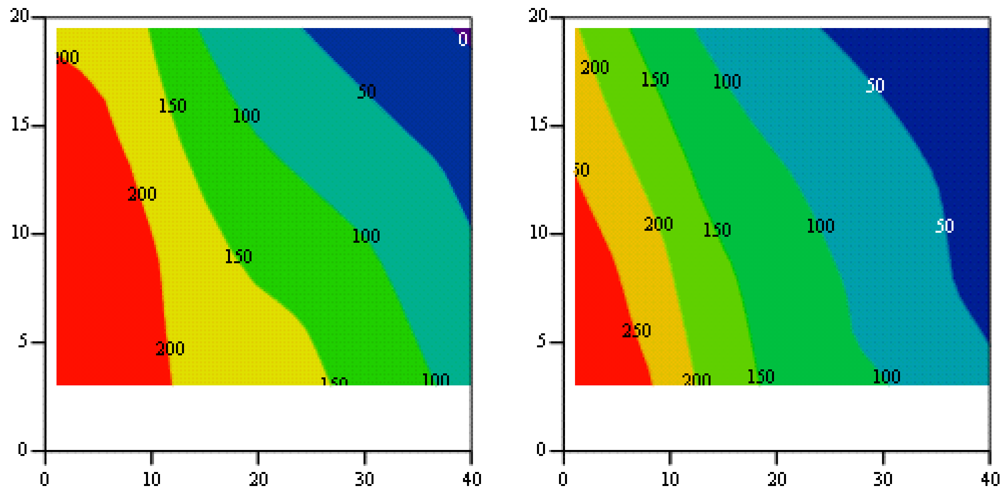



Figure 57. Half-Cell Readings Beam 4A(after 6 months) – Southwest End (left), Northwest End (right)

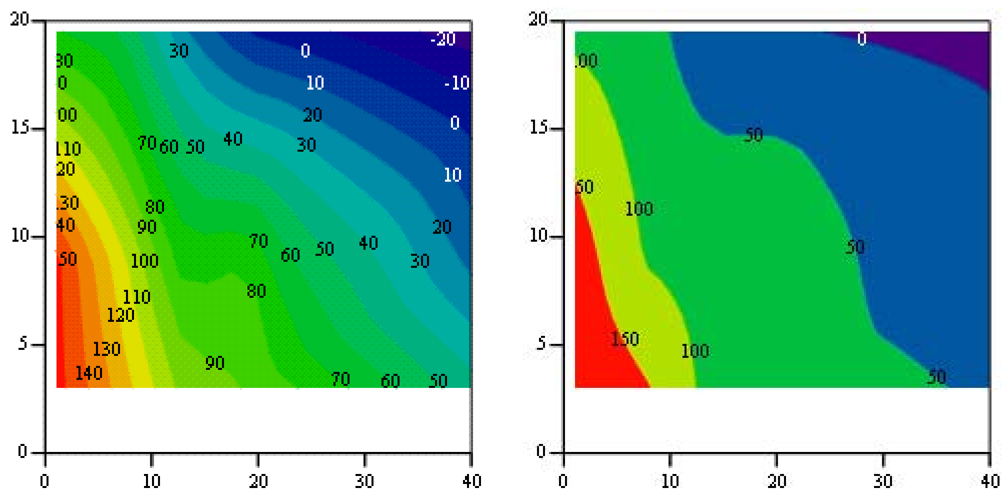



Figure 58. Half-Cell Readings Beam 4B(after 6 months) – Southeast End (left), Northeast End (right)

### 5.1.8 Strain Data

Displacement measurements using a mechanical displacement-measuring device were obtained for each beam end. Throughout the experiment, there were difficulties encountered keeping the points attached to the concrete surface. The brass points routinely would become loose, or become completely detached. Because of this, many of the ends do not have continuous data over the course of the experiment. There were also difficulties encountered obtaining consistent readings with the measurement device. The tip of the device was conical, and hence the measurements could vary depending on the angle the device was placed into the point. Since many of the metal points were located in the path of the salt water, overtime they softened, with many corroding (see Figure 59).

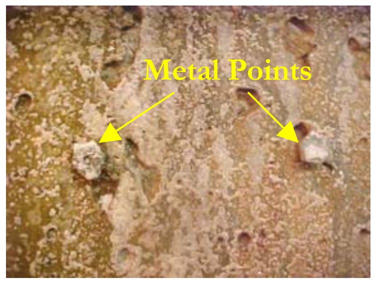



Figure 59. Measurement Points

Due to the softening of the metal, some of the "dimples" or depressions in the center of the points became warped. Hence, the readings would vary depending on where in the "dimple" the tip of the measuring device was placed. It was decided to not consider the gathered strain measurements due to the inconsistencies and inaccuracies of the data.

## 5.2 BEAM CONDITION OBSERVATIONS

### 5.2.1 Beam 1

#### Phase I – Beam 1

An epoxy coating was applied to the west end 1A (pre-coated) of beam 1 prior to the first accelerated corrosion cycle. The east end, 1B, remained untreated for the first exposure cycle. After 6 months, the untreated end (1B) was treated with the same epoxy coating applied to the west end (1A) initially. Figure 60 illustrates the condition of 1A (pre-coated end) after 6 months of exposure. Figure 61 illustrates the condition of the southwest and northwest faces. Figure 62 illustrates the condition of the east end 1B after 6 months of exposure. Figure 63 illustrates the condition of the southeast and northeast faces.

Figure 60. Beam 1: West (pre-coated) Beam-End 1A (after 6 months)

Figure 61. Beam End 1A: Southwest Face (left), Northwest Face (right) (6 months)

Figure 62. Beam End 1B: East Beam-End, initially untreated (after 6 months)

Figure 63. Beam End 1B: Northeast Face (left), Southeast Face (right) (after 6 months)

At the completion of the first exposure cycle the beam-ends had heavy salt residue along the front faces and on some portions of the bottom flanges. Rust stains were also evident along the path of the salt water. No major spalling or cracking was observed. Some flaking of concrete was observed at the corners of the beam. In addition, corrosion products were observed on the exposed tendon ends, and were found to increase in amount over the course of the exposure.

**Phase II – Beam 1**

After 6 months of exposure, both beam-ends were cleaned to remove salt residue and rust products from the face of the beam. Then, a 2-foot section of the east end (1B) surface was ground and thoroughly washed to remove all debris. The surface preparation and surface treatment application information was detailed in section 4.8. The east end (1B) was then treated with the epoxy coating. Figure 64 illustrates the condition of the west end (1A) after 18 months of exposure. Figure 65 illustrates the condition of the southwest side at the west end 1A. Figure 66 illustrates the condition of the east end face and southeast side of 1B (post-coated) after 18 months of exposure. Since the first 6-month exposure cycle did not result in the concrete spalling or significant tendon corrosion (section 5.1.4), the configuration of the saltwater dispersion system was altered slightly to increase the likelihood of corrosion after the second 6-month cycle. Pipes (1 foot long) were added along the north and south sides of each beam end to allow salt water to flow along the side face of the beams. The altered salt-water distribution setup was able to disperse water to both the sides and face of the beams. In addition, due to the new setup all of the beams were exposed to more water at a slightly faster flow rate.


Figure 64. Beam End 1A: West End (pre-epoxy coated)(after 18 months)


Figure 65. Beam End 1A: Southwest Face (after 18 months)


Figure 66. Beam 1: East End 1B (untreated, post-coated) (after 18 months)

### 5.2.2 Beam 2

#### Phase 1 – Beam 2

Both the west (2A) and east (2B) ends remained untreated for the first exposure cycle. After 6 months of exposure, portions of concrete were removed from the east end to facilitate installation of a patch repair. Figure 67 illustrates the condition of the west (untreated end 2A) after 6 months of exposure. Figure 68 illustrates the condition of the southwest face. Figure 69 illustrates the condition of the east (untreated end) after 6 months of exposure. Figure 70 illustrates the condition of the southeast and northeast faces.

Figure 67. Beam End 2A: West End (untreated)(After 6 months)

Figure 68. Beam End 2A: Northwest Face (left)(After 6 months)

Figure 69. Beam End 2B: East Face (untreated, patched)(After 6 months)


Figure 70. Beam End 2B: Northeast Face (left), Southeast Face (right)(After 6 months)

At completion of the first exposure cycle the beams-ends had heavy salt residue along the front faces and on some portions of the bottom flanges. Rust stains were also evident along the path of the salt water. No major spalling or cracking was observed. Some flaking of concrete was observed at the corners or edges of the beam. In addition, corrosion products were observed on the exposed tendon ends, and were found to increase in amount over the course of the exposure.

**Phase II – Beam 2**

After 6 months of exposure, both ends were cleaned to remove salt residue and rust products from the surface of the beam. Since 6 months of exposure did not result in the spalling of concrete, an 18-inch long concrete region of the east end was removed with a chipping hammer for installation of the patch repair (see Figure 71).

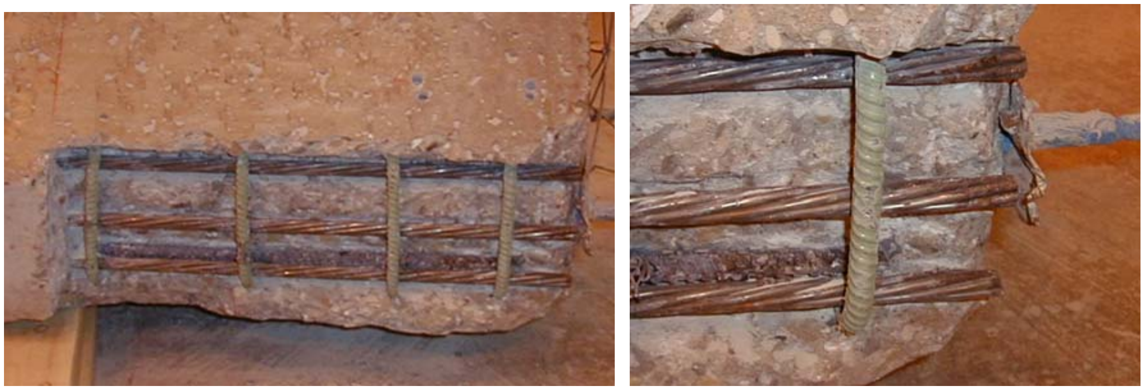


Figure 71. Beam Section Removed for Patch Repair

Figure 72 shows a close-up view of one of the strands. Corrosion products were observed mainly at the end regions of the strands. The build-up of corrosion products was seen to decrease as the distance from the edge of the end increased. The amount of corrosion was less than the researchers had expected. It was determined to change the configuration of the salt-water exposure to facilitate greater exposure on the sides of the beam to salt water.


Figure 72. Close-up View of Tendon from Dissected Beam End

Section 4.8 details the surface preparation and application methods used for the installation of the patch repair. Figure 73 shows the region after application of the bonding agent and after the patch repair material had been placed. The material was installed by a trowel, and pieces of lumber were used to shape the patched region. The region was allowed to cure according to the manufacturer's recommendation before it was re-exposed to the corrosive environment.

Figure 73. Application of Bonding Agent (left) and Patch Material (right)

Figure 74 illustrates the condition of the west (untreated) after 10 months of exposure. Figure 75 illustrates the condition of the southwest and northwest faces after 18 months of exposure.

Figure 74. Beam End 2A: West End (untreated) (After 10 months)

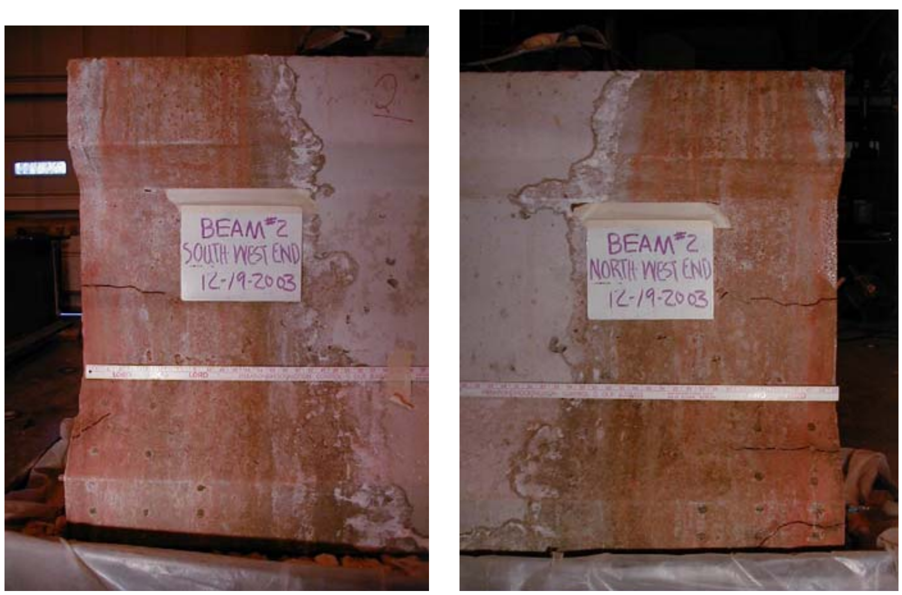



Figure 75. Beam End 2A: Southwest Face (left), Northwest Face (right) (After 18 months)

Figures 76 and 77 illustrate the condition of the southeast and northeast faces (patched) after 18 months of exposure.


Figure 76. Beam End 2B: Southeast Face (untreated, patched) (left), Northeast Face (right) (18 months)


Figure 77. Beam End 2B: Closer views (After 18 months)

After 10 months of corrosion exposure, the beam-ends of beam 2 were experiencing significant rust staining and salt residue. No spalling or major cracking was observed on the untreated (west) end. However, since the end was covered heavily in salt deposits, it was difficult to observe whether or not small hairline cracks were occurring. The patched (east) end experienced no major spalling, but cracks were observed in the patched region of the beam. Also, a vertical crack running the full height of the center section of the southeast end approximately 3 inches from the edge was observed. Increased corrosion products were observed at all exposed steel tendon ends.

At the conclusion of testing (after 18 months of exposure), both ends of beam 2 had developed extensive cracking and corrosion stains were evident. All crack maps are shown in section 5.3 of this report.

### 5.2.3 Beam 3

#### Phase I – Beam 3

A sealer was applied to the west end (pre-sealed) of beam 3 prior to the first accelerated corrosion cycle. The east end remained untreated (post-sealed) for the first exposure cycle. After 6 months, the untreated end was treated with the same sealer applied to the west end initially. Figure 78 illustrates the condition of the west end 3A (pre-sealed) after 6 months of exposure. Figure 79 illustrates the condition of the southwest and northwest faces. Figure 80 illustrates the condition of the east end 3B (untreated post-sealed) after 6 months of exposure. Figure 81 illustrates the condition of the southeast and northeast faces.

Figure 78. Beam End 3A: West End (pre-sealed)(After 6 months)

Figure 79. Beam End 3A: Southwest Face (left), Northwest Face (right)(6 months)

Figure 80. Beam End 3B: East Face (untreated, sealed)(After 6 months)


Figure 81. Beam End 3B: Northeast Face (left), Southeast Face (right)(After 6 months)

At the completion of the first exposure cycle the beam-ends had heavy salt residue along the front faces and on some portions of the bottom flanges. Rust stains were also evident along the path of the salt water.  No major spalling or cracking was observed during the first six months of exposure.  Some flaking of concrete was observed at the corners of the beam.  In addition, corrosion products were observed on the exposed tendon ends, and were found to increase in amount over the course of the exposure.

**Phase II – Beam 3**

After 6 months of exposure, both beam-ends were cleaned to remove salt residue and rust products from the face of the beam.  Then, a 2-foot section of the east end surface was ground and thoroughly washed to remove all debris.  The surface preparation and surface treatment application information was detailed in section 4.8.  The east end of beam 3 was then treated with the silane penetrating sealer.  Figure 82 illustrates the condition of the west (pre-sealed end) after 10 months of exposure.  Figure 83 illustrates the condition of the end face of 3A after 18 months of exposure.  Figure 84 shows the condition of southwest face of beam end 3A. Figure 85 and 86 illustrate the condition of the beam end 3B (post-sealed) after 18 month.

Figure 82. Beam End 3A: West End (pre-sealed) (After 10 months)

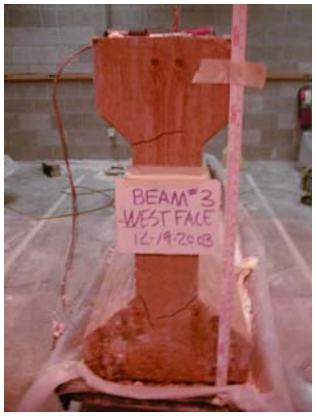




Figure 83. Beam End 3A: West End (pre-sealed)(After 18 months)


Figure 84. Beam End 3A: Southwest Face (After 18 months)


Figure 85. Beam End 3B: East End (After 18 months)


Figure 86. Beam End 3B: Northeast Face (left), Southeast Face (right) (After 18 months)

After approximately 10 months of exposure, the ends of beam 3 were experiencing significant rust staining and salt residue deposits. No spalling was observed on either of the beam-ends at that time. However, since the ends were covered heavily in salt deposits, it was difficult to observe whether or not small hairline cracks were occurring. Several cracks were observed on the post-sealed (east) end of the beam.  A large horizontal crack on the northeast bottom flange, about 10 inches in length, was observed.  Also, a vertical crack on the bottom flange of the east face was observed.

At the conclusion of testing (after 18 months of exposure), both ends of beam 3 had developed extensive cracking and corrosion stains were evident. All crack maps are shown in section 5.3 of this report.

### 5.2.4 Beam 4

#### Phase I – Beam 4

Both the west and east ends remained untreated for the first exposure cycle.  After 6 months of exposure, the FRP system was applied to the east end and the polymer (resin) was applied to the west end of the beam.  Figure 87 illustrates the condition of the west (untreated end) after 6 months of exposure.  Figure 88 illustrates the condition of the southwest and northwest faces.  Figure 89 illustrates the condition of the east (untreated end) after 6 months of exposure.  Figure 90 illustrates the condition of the southeast and northeast faces.

Figure 87. Beam End 4A: West End (untreated, post-polymer)(After 6 months)

Figure 88. Beam End 4A: Southwest Face (left), Northwest Face (right)(After 6 months)

Figure 89. Beam End 4B: East Face (untreated, post-FRP)(After 6 months)

Figure 90. Beam End 4B: Northeast Face (left), Southeast Face (right)(After 6 months)

At completion of the first exposure cycle the beams-ends had heavy salt residue along the front faces and on some portions of the bottom flanges.  Rust stains were also evident along the path of the salt water. No major spalling or cracking was observed. Some flaking of concrete was observed at the corners or edges of the beam. In addition, corrosion products were observed on the exposed tendon ends, and were found to increase in amount over the course of the exposure.

**Phase II – Beam 4**

After 6 months of exposure, both beam-ends were cleaned to remove salt residue and rust products from the face of the beam. Then, a 2-foot section of both end surfaces were ground and thoroughly washed to remove all debris. The surface preparation and surface treatment application information was detailed in section 4.8. The east end was then treated with the FRP system and the west end was treated with the polymer (resin). Figure 91 illustrates the condition of the west end 4A after 10 months of exposure. Figure 92 illustrates the condition of the west end 4A after 18 months of exposure. Figure 93 illustrates the condition of the east end 4B (post FRP) after 18 months of exposure.

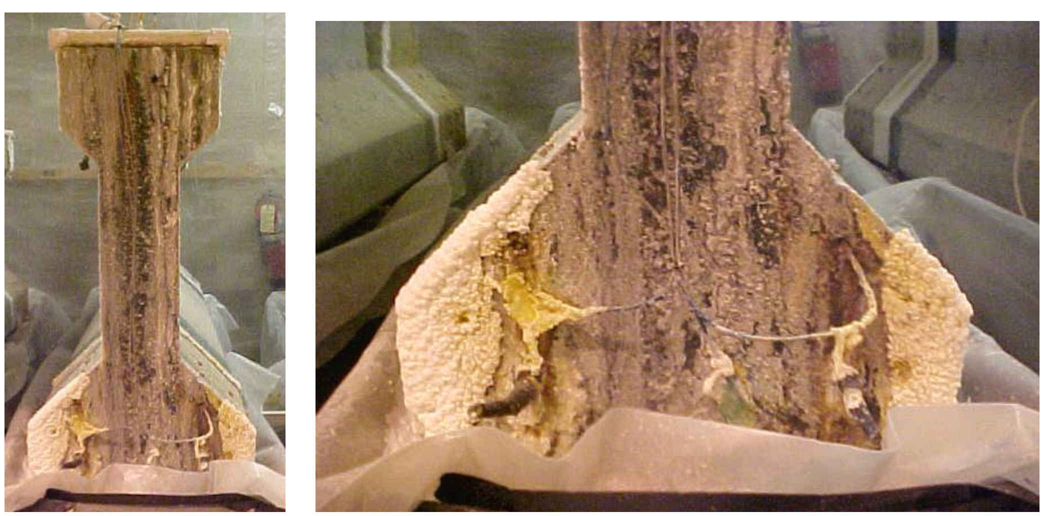


Figure 91. Beam End 4A: West End (untreated, post-polymer) (After 10 months)


Figure 92. Beam End 4A: Southwest Face (left), Northwest Face (right) (After 18 months)


Figure 93. Beam End 4B: Northeast (untreated, post-FRP) (left), Southeast (right) (18 months)

No spalling or major cracking was observed on either of the beam-ends at the end of 18 months of exposure.

### 5.2.5 Beam 5

**Phase I – Beam 5**

A polymer (resin) was applied to the west end 5A (pre-polymer) of beam 5 prior to the first accelerated corrosion cycle. In addition, the FRP system was applied to the east end 5B (pre-FRP) of beam 5 before the first exposure cycle. Figure 94 illustrates the condition of the west end 5A (pre-polymer end) after 6 months of exposure. Figure 95 illustrates the condition of the southwest and northwest faces. Figure 96 illustrates the condition of the east end 5B (post-FRP end) after 6 months of exposure. Figure 97 illustrates the condition of the southeast and northeast faces.

Figure 94. Beam End 5A: West End (pre-polymer)(After 6 months)

Figure 95. Beam End 5A: Southwest Face (left), Northwest Face (right)(After 6 months)

Figure 96. Beam End 5B: East Face (pre-FRP)(After 6 months)

Figure 97. Beam End 5B: Northeast Face (left), Southeast Face (right)(After 6 months)

No major spalling or cracking was observed at the end of 6 months of exposure.

**Phase II – Beam 5**

After 6 months of exposure, both beam-ends were cleaned to remove salt residue and rust products from the face of the beam. No additional actions were taken for both beam-ends. Figure 98 illustrates the condition of the west (pre-polymer end) after 10 months of exposure. Figure 99 illustrates the condition of the southwest and northwest faces of beam 5 after 18 months of exposure. Figure 100 illustrates the condition of the southeast and northeast (pre-FRP) faces after 18 months of exposure.

Figure 98. Beam End 5A: West End (pre-polymer) (After 10 months)


Figure 99. Beam End 5A: Southwest Face (left), Northwest Face (right) (18 months)


Figure 100. Beam End 5B: Northeast Face (pre-FRP) (left), Southeast Face (right) (18 months)

After 18 months of exposure, no spalling or major cracking was observed on either of the beam-ends. Crack maps for all beams are shown in section 5.3.

## 5.3 CRACK MAPS

### 5.3.1 Beam 1

Crack maps for all beam-ends were obtained at the completion of the first 6 months of exposure and at the conclusion of all tests (18 months). Figures 101 and 102 illustrate the crack maps for the west (1A, pre-coated) and east (1B, untreated, post-coated) ends. The crack widths on the west face varied from 0.005 to 0.010 inches. The northwest face crack width was 0.005 inches and the southwest face crack width was 0.010 inches. The crack width on the east face was measured to be equal to 0.005 inches. No cracks were observed on the northeast and southeast faces.

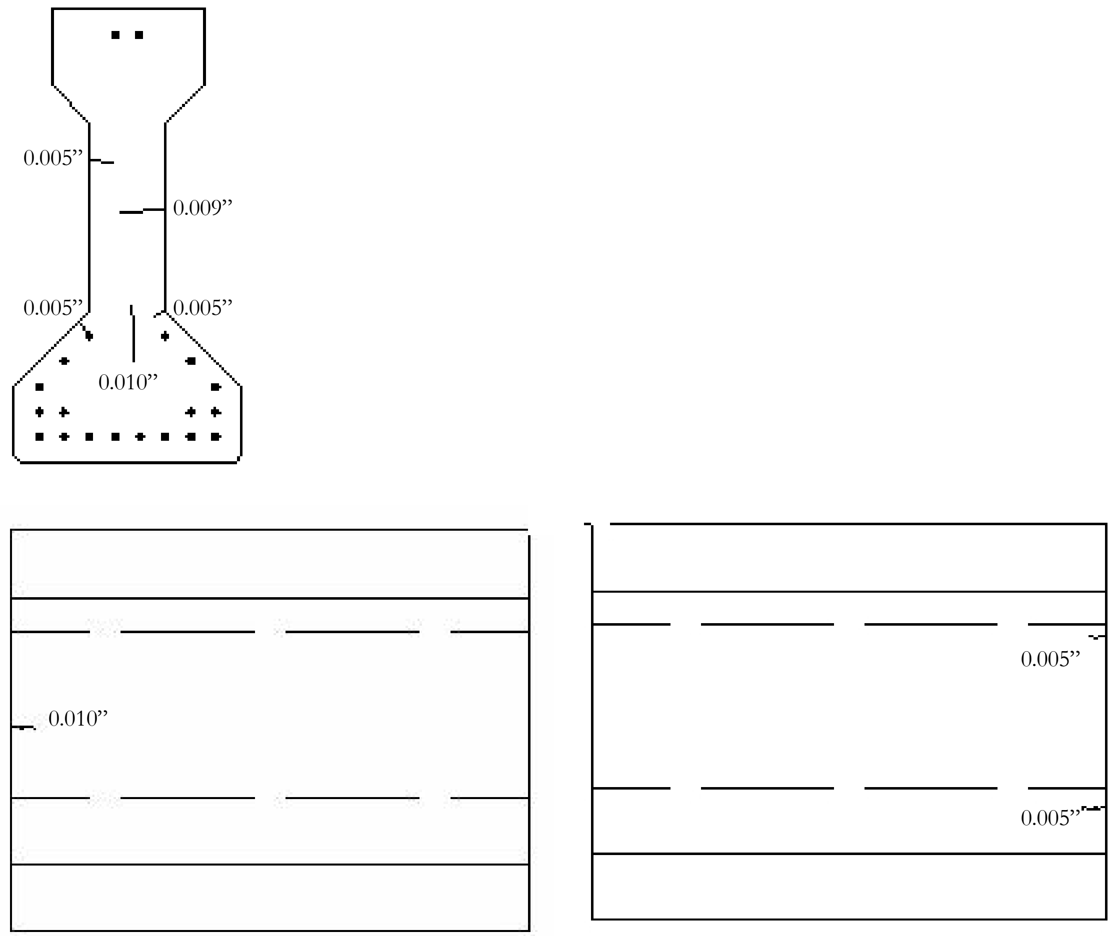



Figure 101. Beam End 1A: West End (top), Southwest (left), Northwest (right) (6 months)

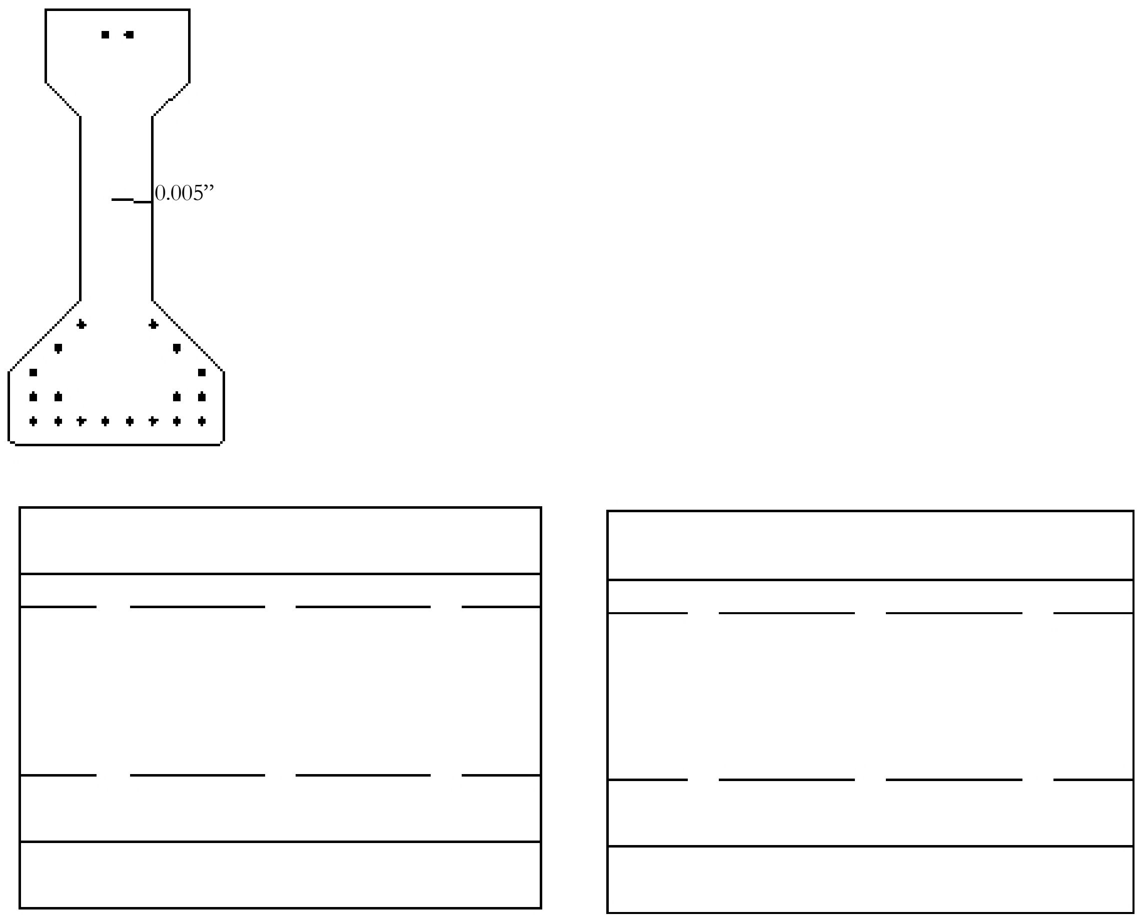



Figure 102. Beam End 1B: East End (top), Southeast Face (left), Northeast Face (right) (6 months)

Figures 103 and 104 show crack maps for the 1A and 1B ends at the conclusion of testing (18 month). There is only a slight progression of cracking on the northwest side of 1A from 6 months of exposure to 18 months. However, the 1B end did develop extensive new cracks at the end of the 18-month exposure period. This is expected as 1B was subjected to 6 months of unprotected exposure to saltwater before application of epoxy coating.

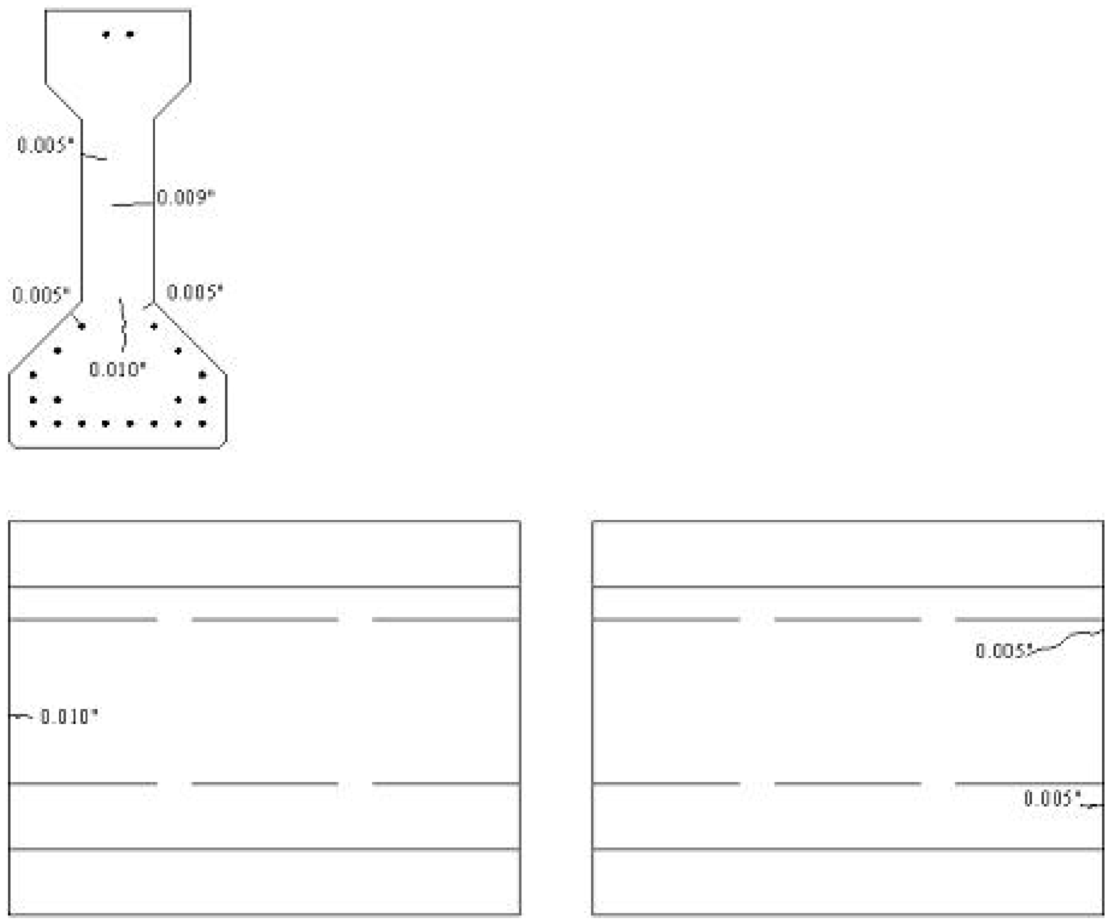



Figure 103. Beam End 1A: West End (top), Southwest (left), Northwest (right) (18 months)

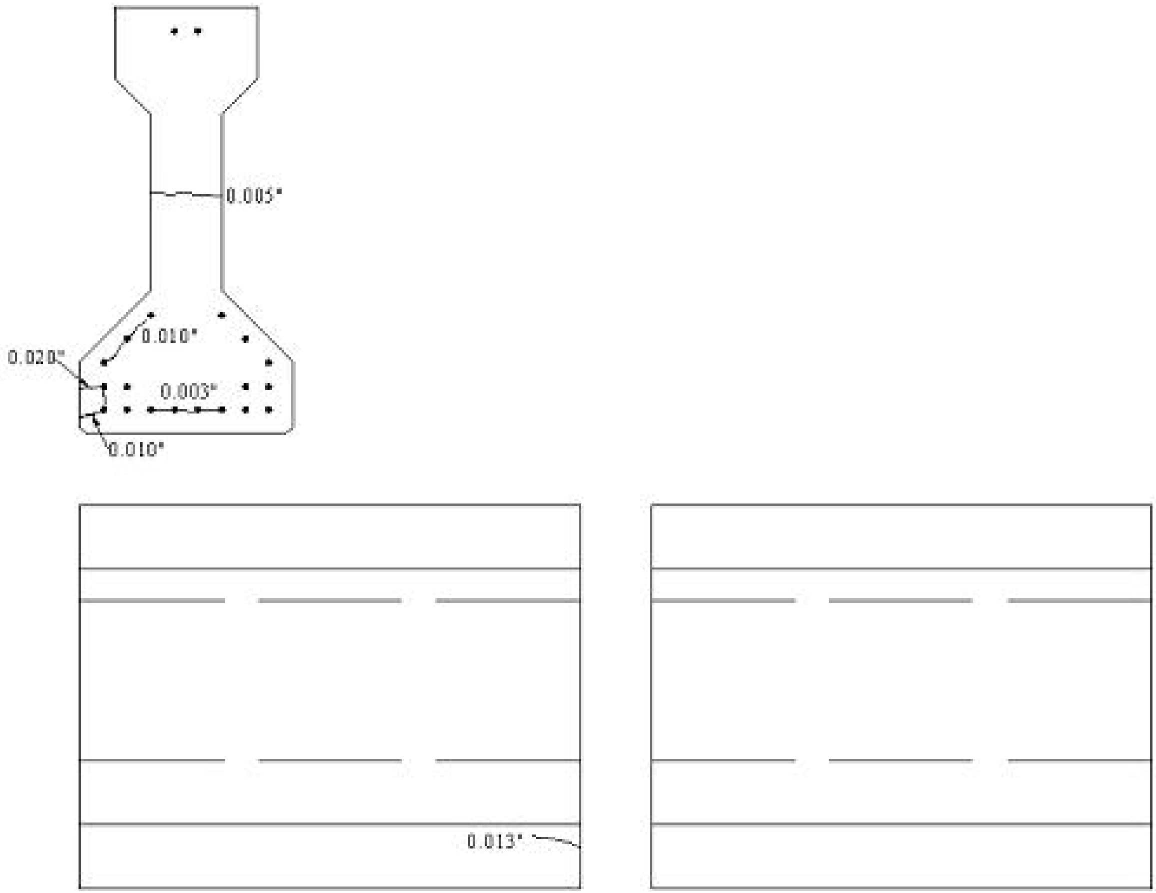



Figure 104. Beam End 1B: East End (top), Southeast (left), Northeast (right) (18 months)

### 5.3.2 Beam 2

Crack maps for both beam-ends were obtained at the completion of the first 6 months of exposure and at the conclusion of all tests. Figures 105 and 106 illustrate the crack maps for the west end 2A (untreated) and east end 2B (untreated, patched) at the end of 6 months of exposure. The crack widths on the west face varied from 0.003 to 0.005 inches. The northwest face crack width was 0.002 inches and the southwest face crack width was 0.002 inches. The crack widths on the east face ranged between 0.002 and 0.003 inches. The southeast crack widths were between 0.002 and 0.003 inches. No cracks were observed on the northeast face. Crack maps after 18 months of exposure for beam ends 1A and 1B are shown in figures 107 and 108, respectively.

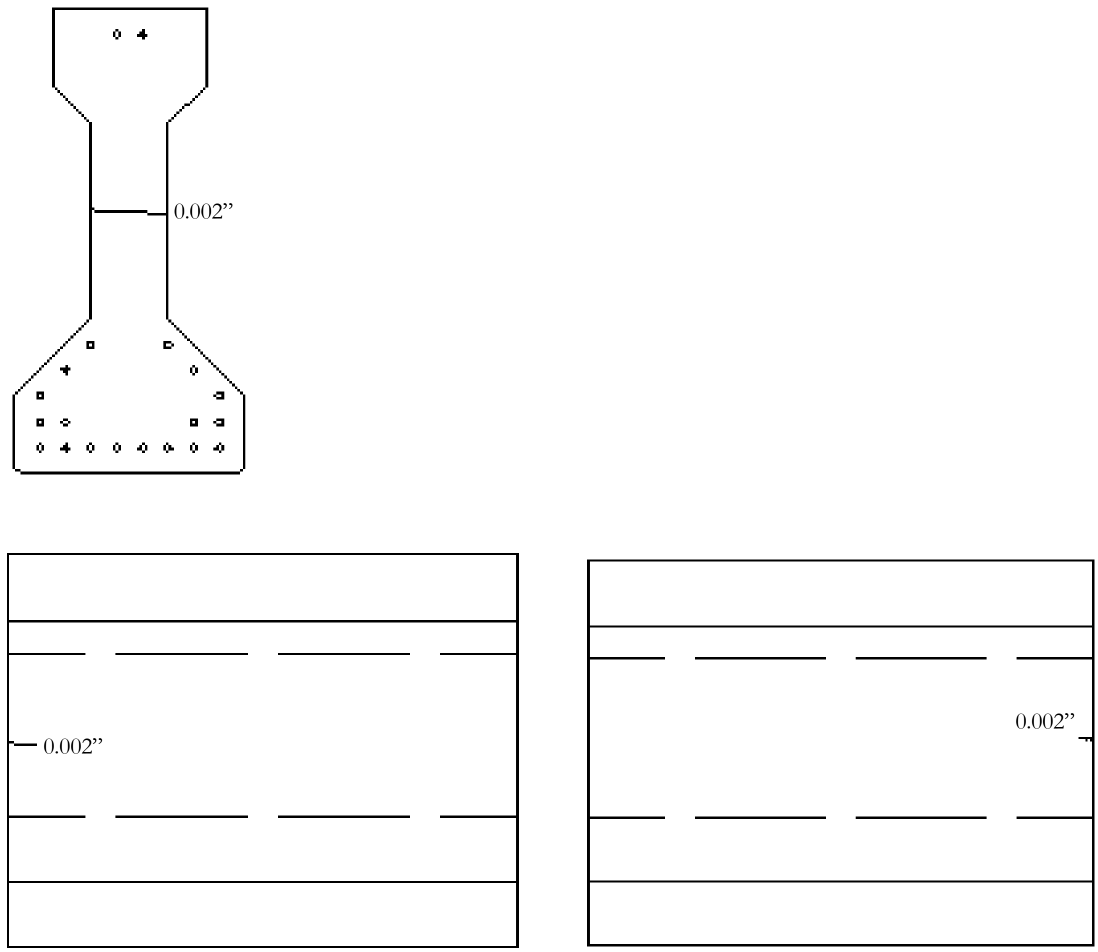



Figure 105. Beam End 2A: West End (top), Southwest (left), Northwest (right)(6 months)

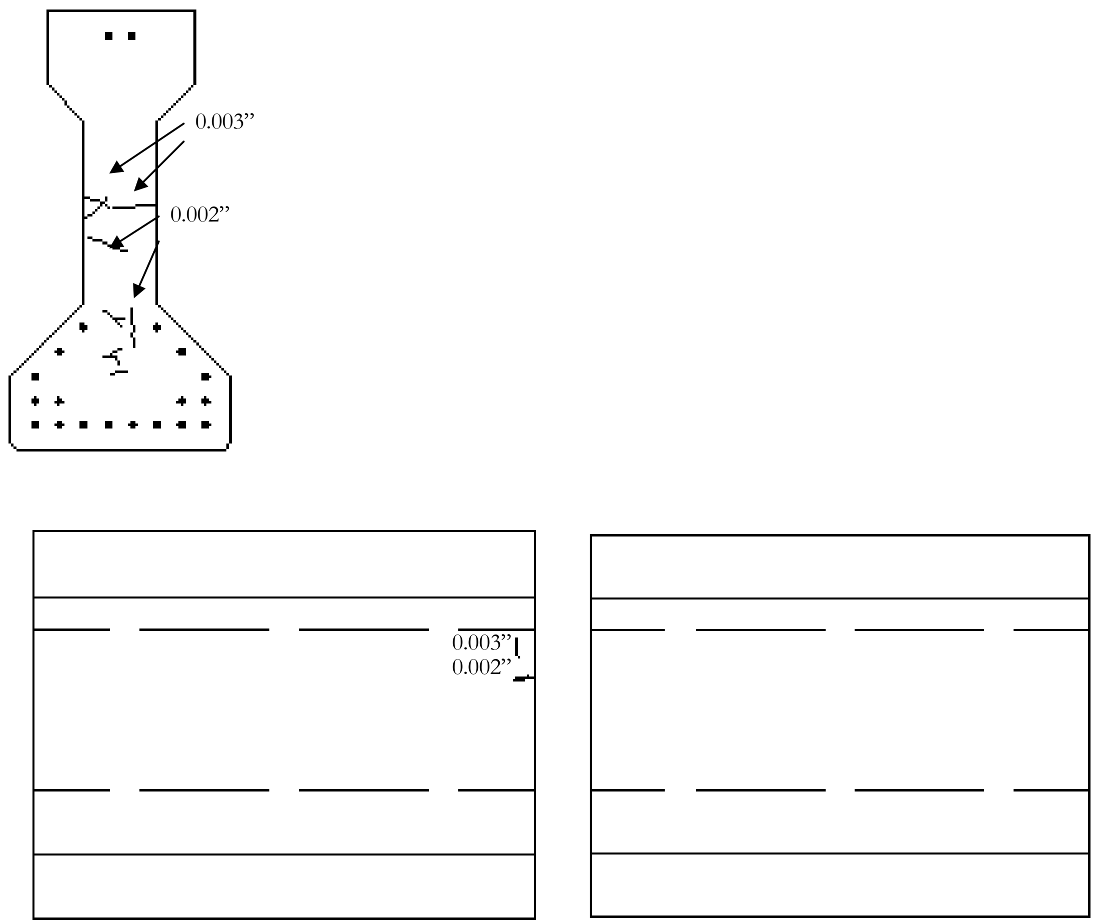



Figure 106. Beam End 2B: East End (top), Southeast (left), Northeast (right) (6 months)

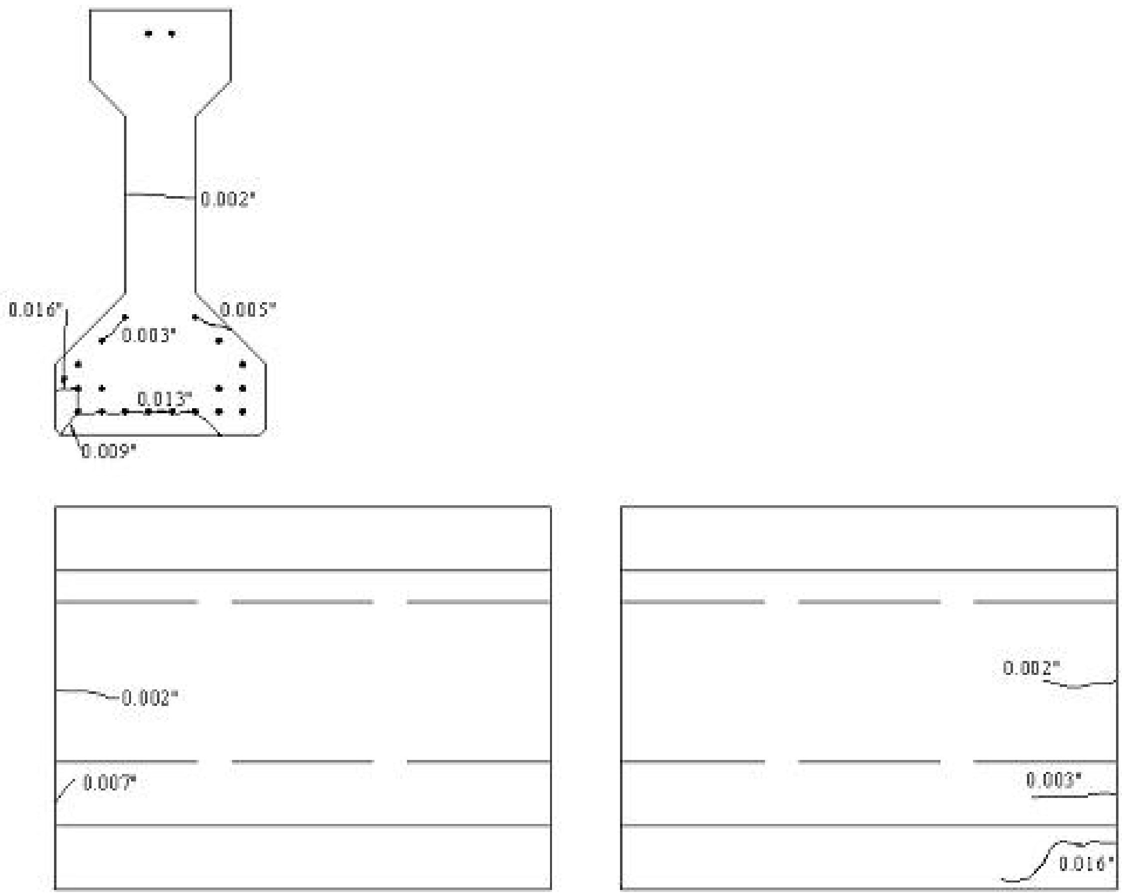



Figure 107. Beam End  2A: West End (top), Southwest (left), Northwest (right)(18 months)

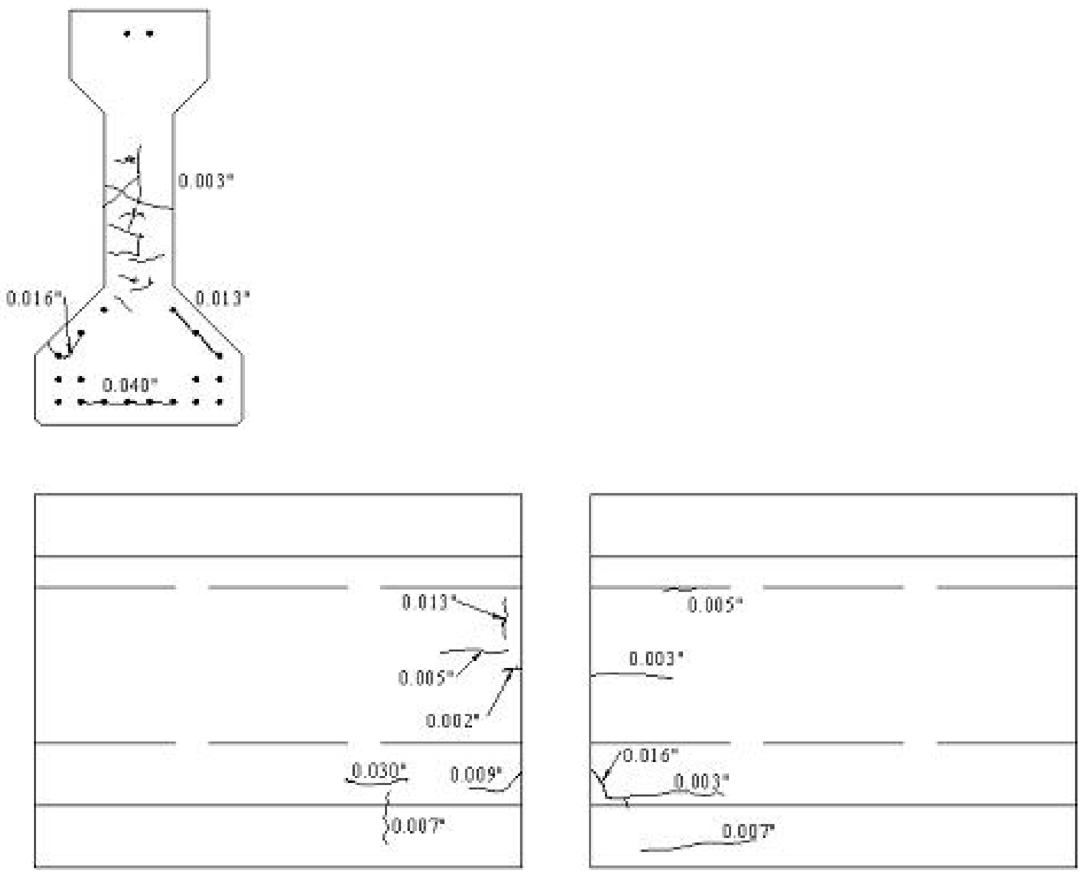



Figure 108. Beam End 2B: East End (top), Southeast (left), Northeast (right)(18 months)

It is clear that cracking grew between 6 and 18 months, especially for beam end 2B (patched end). The cracks between strands indicate the onset of spalling. The crack sizes are also large.

### 5.3.3 Beam 3

Crack maps for both beam-ends were obtained at the completion of the first 6 months of exposure and the conclusion of all tests. Figures 109 and 110 illustrate the crack maps for the west end 3A (pre-sealed) and east end 3B (untreated, post-sealed). After 6 months, the crack widths on the west face varied from 0.003 to 0.005 inches. The northwest face crack widths ranged between 0.003 and 0.010 inches and the southwest face crack widths were between

0.002 and 0.020 inches. The crack widths on the east face ranged between 0.002 and 0.010 inches. The northeast crack widths were between 0.002 and 0.005 inches. No cracks were observed on the southeast face after 6 months of exposure. Figure 111 and 112 show crack maps after 18 months of exposure for 3A and 3B, respectively. Again, crack growth was clearly evident in both beam-ends.

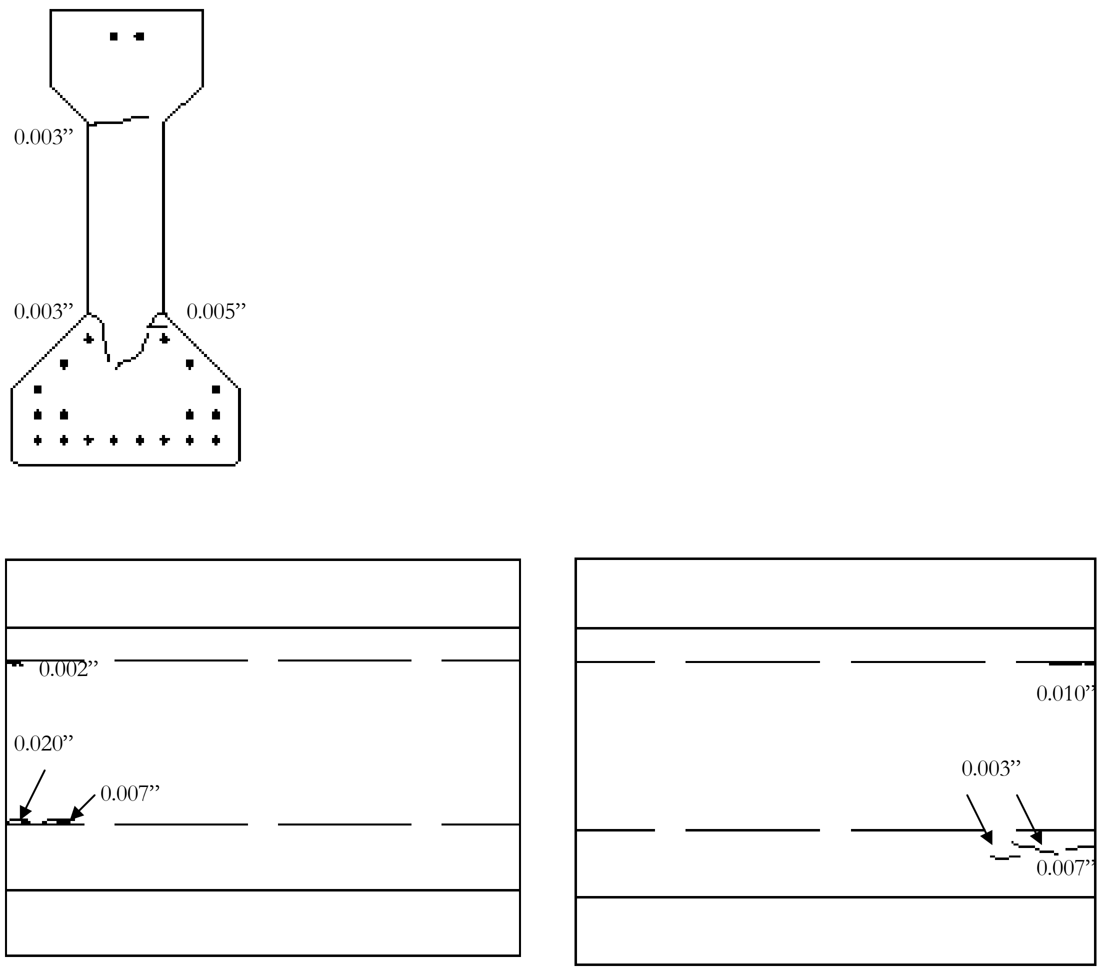



Figure 109. Beam End 3A: West End (top), Southwest (left), Northwest (right) (6 months)

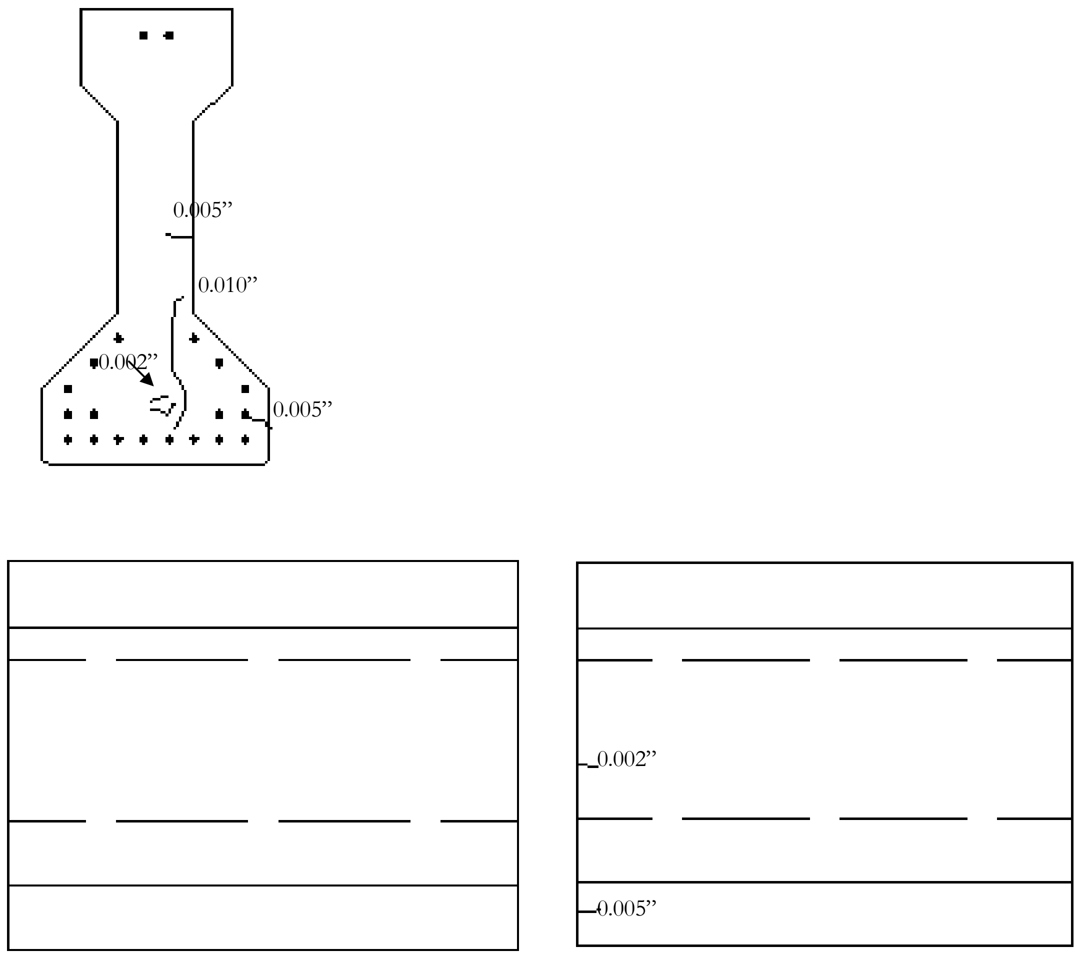



Figure 110. Beam End 3B: East End (top), Southeast (left), Northeast (right) (6 months)

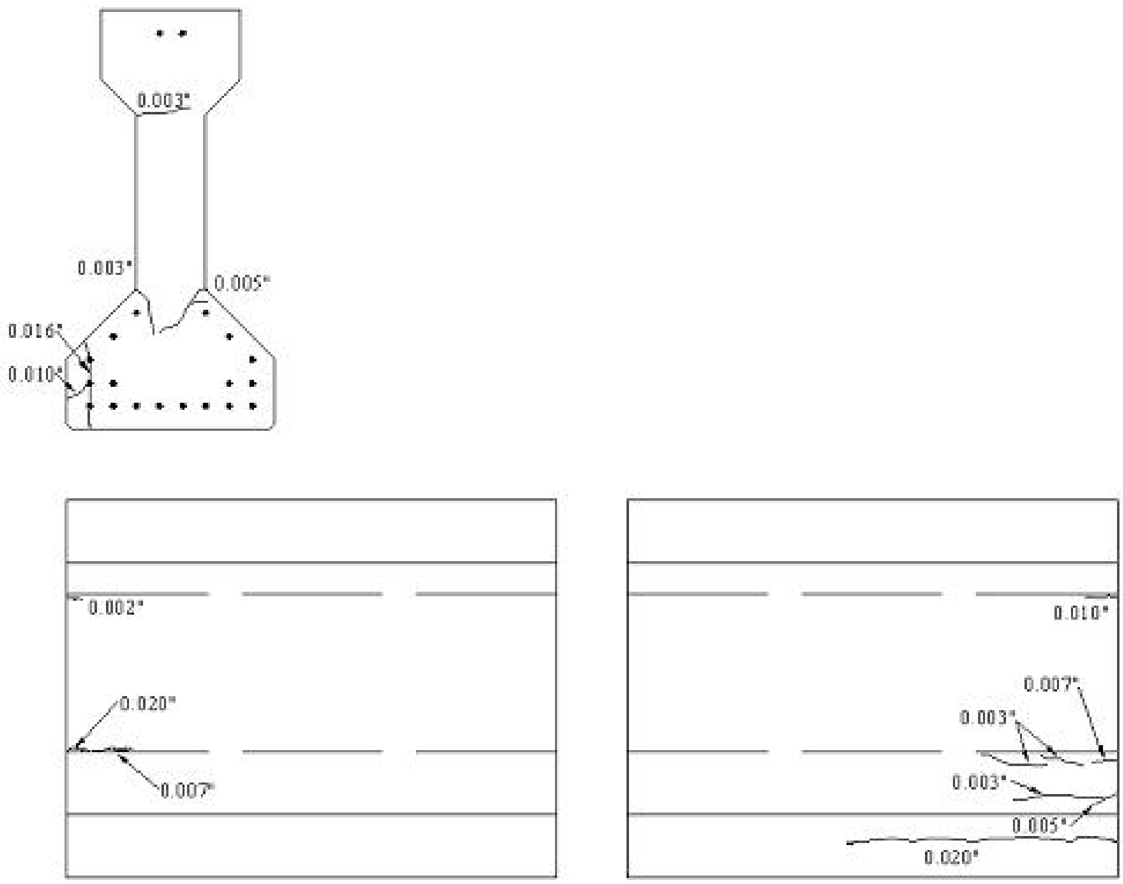



Figure 111. Beam End 3A: West End (top), Southwest (left), Northwest (right) (18 months)

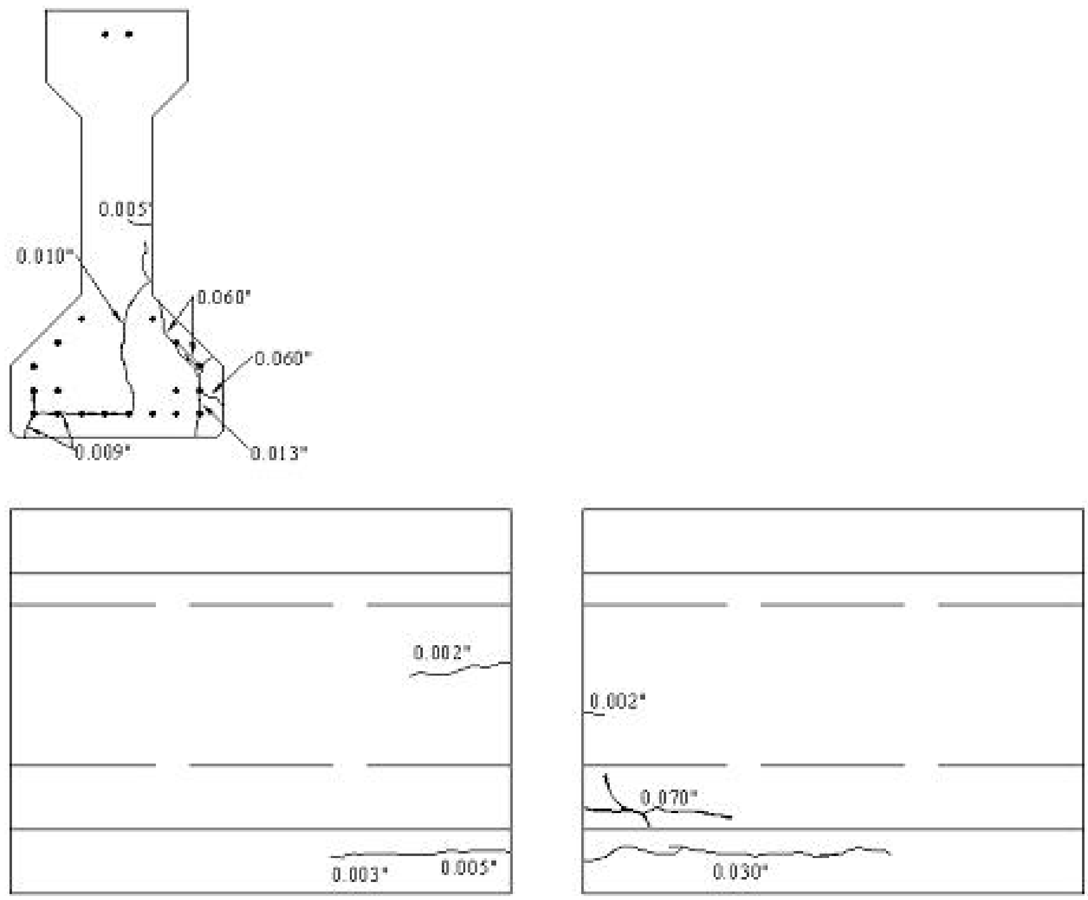



Figure 112. Beam End 3B: East End (top), Southeast (left), Northeast (right) (18 months)

### 5.3.4 Beam 4

Crack maps for both beam-ends were obtained at the completion of the first 6 months of exposure and at the conclusion of all tests. Figures 113 and 114 illustrate the crack maps for the west end 4A (untreated, post-polymer) and east end 4B (untreated, post-FRP). The crack widths on the west face varied from 0.003 to 0.009 inches. The northwest face crack width was 0.002 inches and the southwest face crack width was 0.005 inches. The crack widths on the east face ranged between 0.002 and 0.003 inches. The northeast crack width was 0.003 inches. No cracks were observed on the southeast face after 6 months of exposure.

Figures 115 and 116 show crack maps after 18 months of exposure for the 4A and 4B beam ends, respectively. Additional cracking developed at the end face of 4A from 6 months to 18 months.

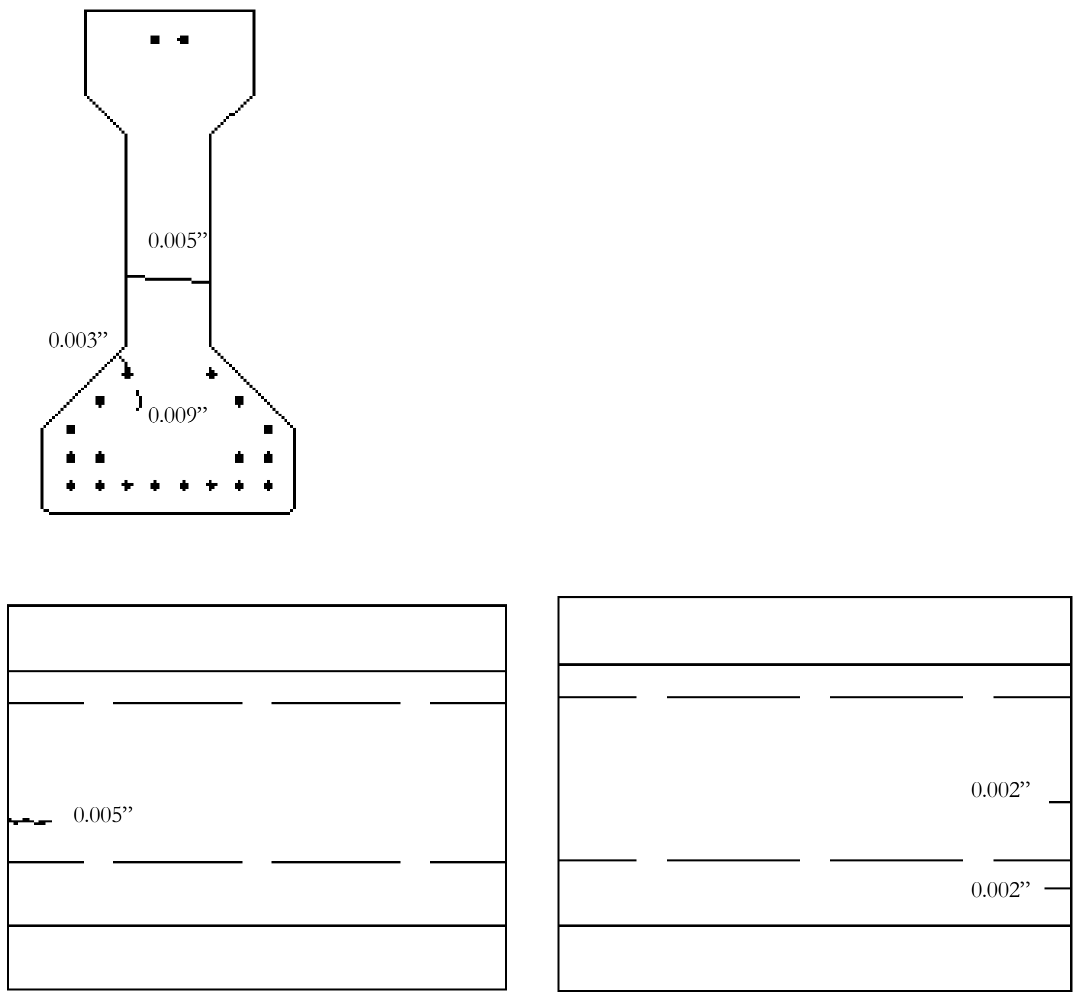



Figure 113. Beam End 4A: West (top), Southwest (left), Northwest (right) (6 months)

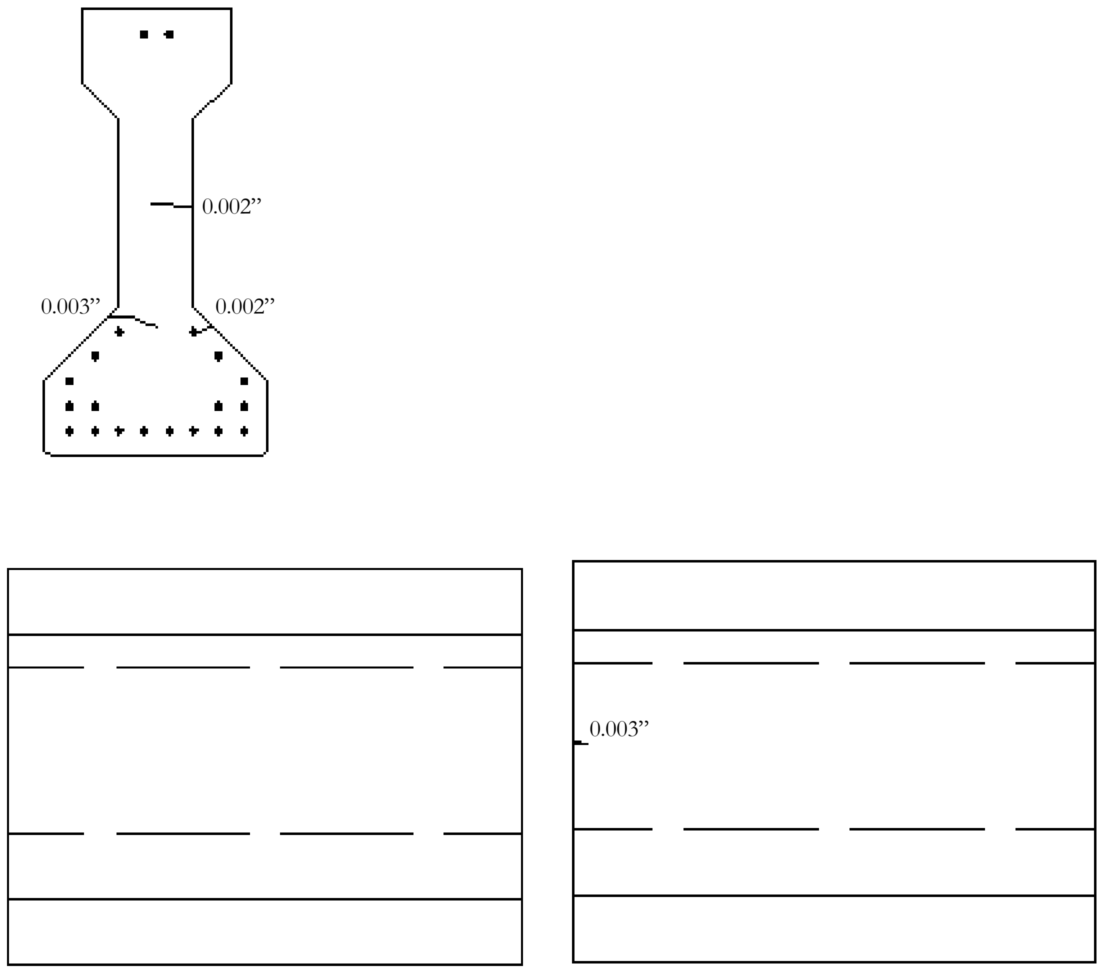



Figure 114. Beam End 4B: East (top), Southeast (left), Northeast (right) (6 months)

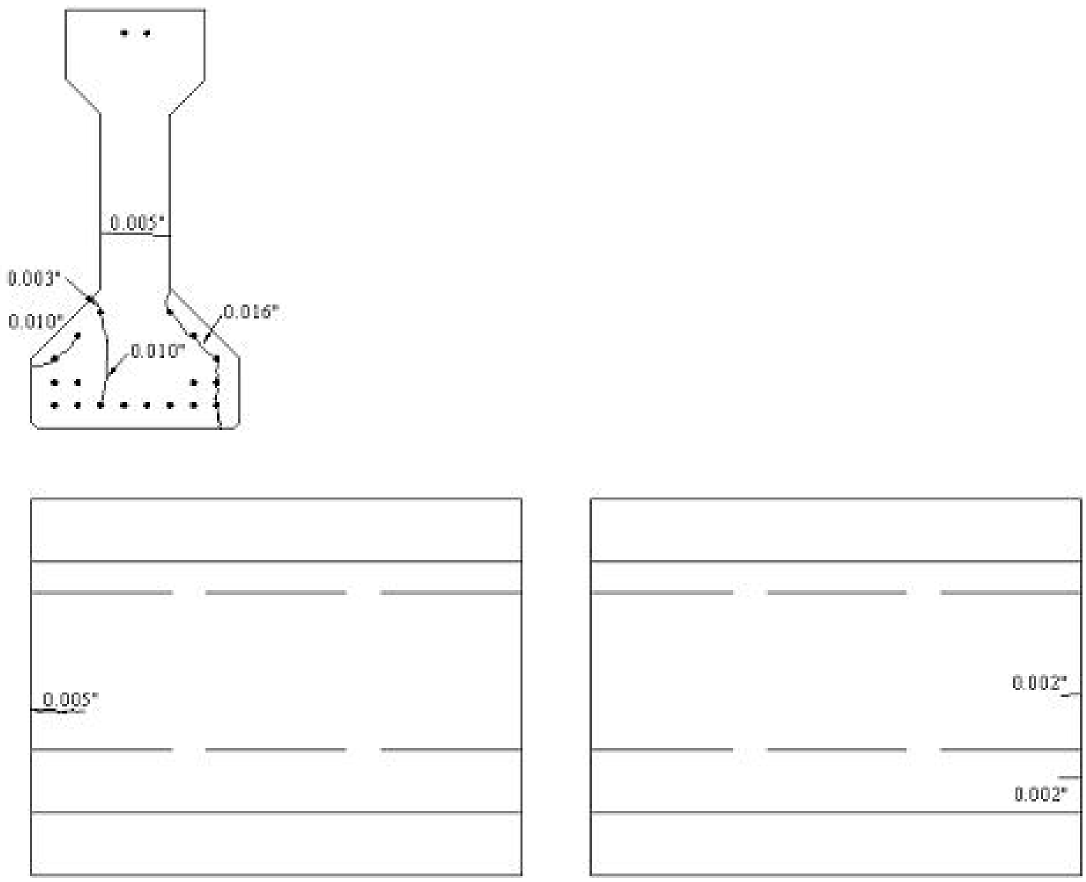



Figure 115. Beam End 4A: West (top), Southwest (left), Northwest (right) (18 months)

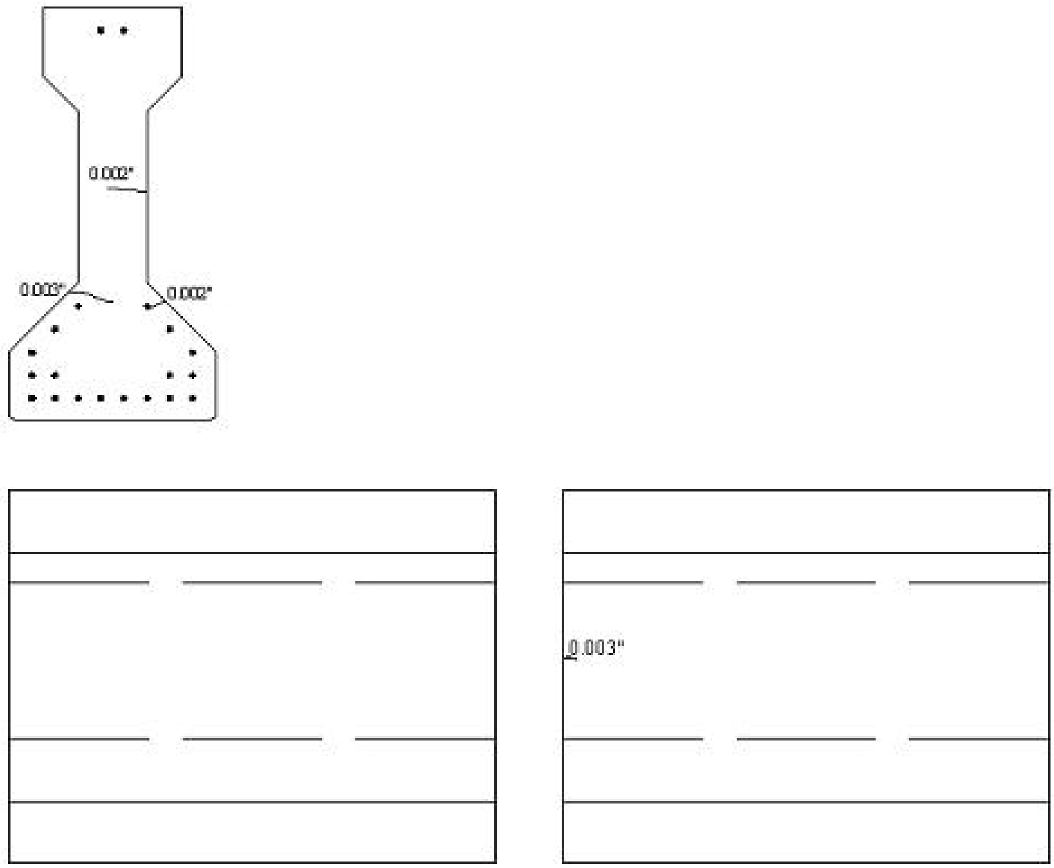



Figure 116. Beam End 4B: East (top), Southeast (left), Northeast (right) (18 months)

### 5.3.5 Beam 5

Both ends of beam 5 were coated with polymer resin (5A) or FRP wrap (5B) from the first day. Cracking was not observed in 5A, and was not detectable because of FRP wrap in 5B. Therefore crack mapping is not shown here.

### 5.3.6 Comparison of Crack Map Results

To compare various crap maps together, a rating scale of 1 to 8 was utilized with 1 representing least (almost no) cracking, and 8 representing the most extensive cracking observed. The range 1 to 8 was selected because the other comparative scale utilized for corrosion comparisons (the PCI reference method discussed in next section of this report) also uses a 1 to 8 numerical scale. Table 32 shows the rating numbers given to various beam-ends at the conclusion of all tests (after 18 months of exposure). The shaded rows in Table 32 indicate treatment after 6 months of exposure.

Table 32. Numerical Rating* of Extent of Cracking Observed After 18 Months of Exposure

| BeamEnd | Description | Rating |
|---|---|---|
| 1A | Epoxy Coated From Day 1 | 2 |
| 1B | Epoxy Coated After 6 Months of Exposure | 4 |
| 2A | No Treatment Applied | 6 |
| 2B | Patch Repair After 6 Months of Exposure | 7 |
| 3A | Silane Sealer Applied from Day 1 | 5 |
| 3B | Silane Sealer Applied After 6 Months of Exposure | 8 |
| 4A | Polymer Resin Coating Applied After 6 Months of Exposure | 3 |
| 4B | FRP Wrap Applied After 6 Months of Exposure | 1 |
| 5A | Polymer Resin Coating Applied From Day 1 | 1 |
| 5B | FRP Wrap Applied From Day 1 | 1 |

*Rating is based on 1 –8 scale, 1 indicating least cracking, 8 most extensive cracking
Shaded rows indicate beam-ends that were treated after 6 months of exposure

It is clear from Table 32 that among beam-ends treated from the first day of exposure, beam-ends 5B, 5A, 1A, 3A, and 2A were ranked from best to worst. The FRP wrap and polymer resin coatings applied from Day 1 provided better performance as far as extent of cracking is concerned. For beam-ends treated after 6 months of exposure, the least to most extensive cracks were observed in 4B, 4A, 1B, 2B and 3B. Again, FRP wraps and polymer resin coating performed the best in this case.

## 5.4 DISSECTION OF BEAM ENDS

At the conclusion of 18 months of exposure to accelerated corrosion environment, all beam-ends were partially dissected to closely examine the condition of strands in the bottom flanges. Concrete in the southern half of bottom flanges in all beam-ends was removed using a jackhammer. Two strands were removed from each dissected beam-end. These strands represented the worst condition, with respect to corrosion, observed along the sloping / vertical sides of the flange and along the bottom layer of strands in the exposed area. One strand was removed from the sloping area and the other from the exposed bottom layer of strands. The corrosion conditions of the removed strands were categorized based on a visual ranking proposed by Sason in a PCI Journal paper [55]. In the PCI method, the surface condition of strands is compared against a set of pictures of strands with various corrosion states. Based on this comparison, a numerical rating from 1 to 8 (1 best, 8 worst) is given to each strand sample removed.

Figures 117 thru 128 show the condition of strands after dissection for all beam-ends. A numerical rating of bottom strand samples based on the PCI reference [55] are given in Table 33. Among the beam-ends treated from the first day, the FRP wrap and polymer resin coating were rated the best. For beam-ends treated after 6 months of exposure, the Silane sealer and polymer resin coating were judged the best with respect to strand corrosion.

Table 33. Numerical Rating* of the Extent of Corrosion Observed on Strands After 18 Months of Exposure

| Beam End | Description | Side Strand | Bottom Strand | Ave. Rating |
|---|---|---|---|---|
| 1A | Epoxy Coated From Day 1 | 2 | 4 | 3 |
| 1B | Epoxy Coated After 6 Months of Exposure | 7 | 7 | 7 |
| 2A | No Treatment Applied | 4 | 7 | 5.5 |
| 2B | Patch Repair After 6 Months of Exposure | 8 | 8 | 8 |
| 3A | Silane Sealer Applied from Day 1 | 2 | 5 | 3.5 |
| 3B | Silane Sealer Applied After 6 Months of Exposure | 5 | 6 | 5.5 |
| 4A | Polymer Resin Coating Applied After 6 Months Exp. | 6 | 6 | 6 |
| 4B | FRP Wrap Applied After 6 Months of Exposure | 7 | 7 | 7 |
| 5A | Polymer Resin Coating Applied From Day 1 | 2 | 2 | 2 |
| 5B | FRP Wrap Applied From Day 1 | 1 | 3 | 2 |

*Rating is based on 1 –8 scale, 1 indicating least corrosion, 8 most extensive corrosion
Shaded rows indicate beam-ends that were treated after 6 months of exposure

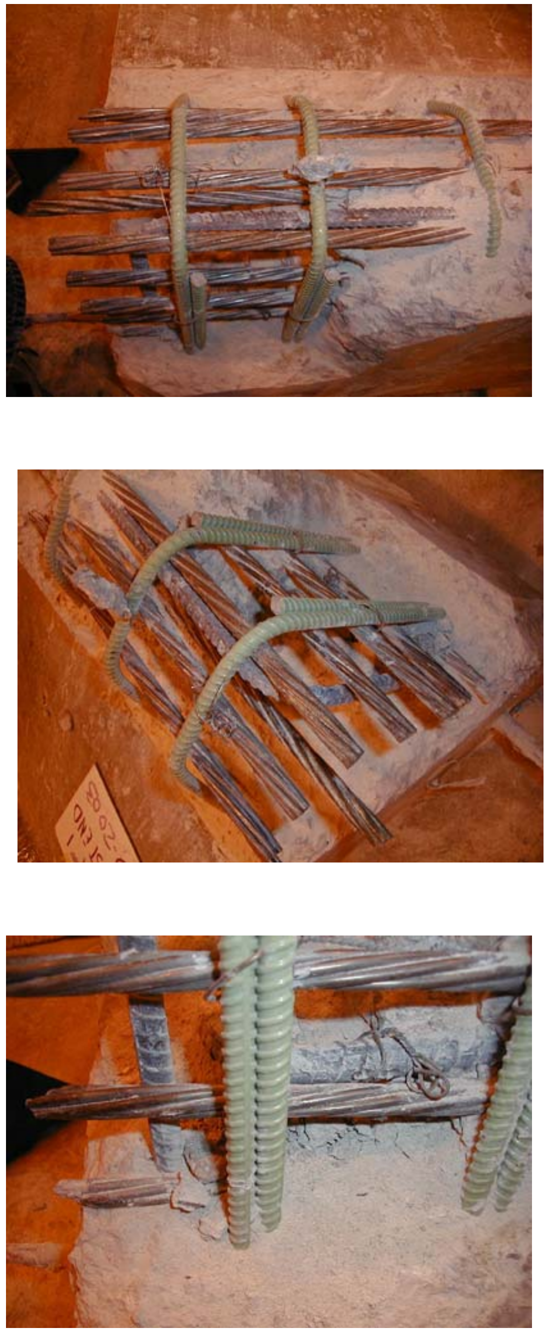


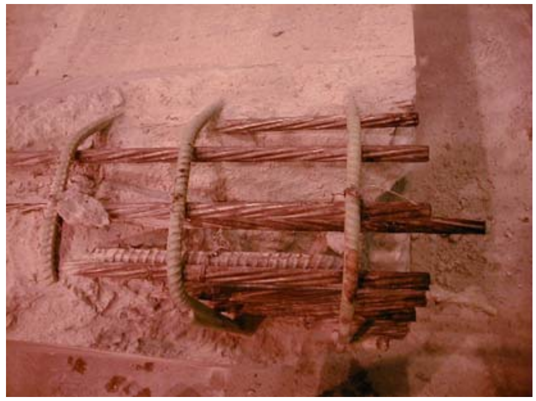
Figure 117. Beam End 1A – Treated With Epoxy Coating From Day 1

Figure 118. Beam End 1B – Treated With Epoxy Coating After 6 Months of Exposure

Figure 119. Beam End 2A – Not Treated At All

Figure 120. Beam End 2B – Patch Repair After 6 Months of Exposure

Figure 121. Beam End 3A – Treated With Silane Sealer From Day 1



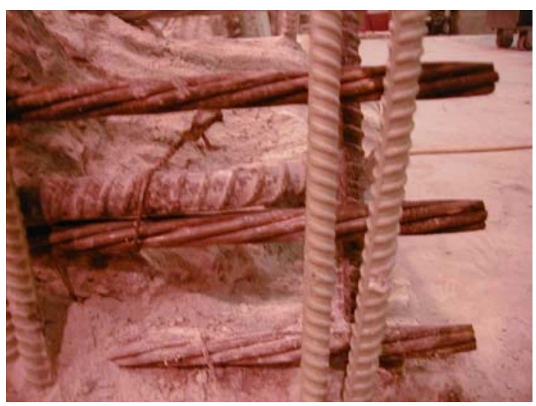


Figure 122. Beam End 3B – Treated With Silane Sealer After 6 Months of Exposure

Figure 123. Beam End 4A – Treated With Polymer Resin Coating After 6 Months of Exposure

Figure 124. Beam End 4B – Treated With FRP Wrap After 6 Months of Exposure

Figure 125. Beam End 5A – Treated With Polymer Resin Coating From Day 1

Figure 126. Beam End 5B – Treated With FRP Wrap From Day 1


Figure 127. Comparison of Strands with Respect to Corrosion


Figure 128. Comparison of Strands with Respect to Corrosion

## 5.5 ASSESSMENT OF RESULTS

To compare the performance of various beam-ends, it was decided to select three performance indicators: chloride intrusion, extent of cracking, and extent of corrosion. All these three parameters were previously given a numerical rating of 1 (best) to 8 (worst). The ratings given were based on visual observations, except for the chloride levels, which were based on actual chloride measurements. The corrosion ratings were based Sason's rating system published in PCI Journal [55]. Table 34 lists all numerical ratings (from Tables 30, 32, and 33) and the sum of the three ratings for each beam-end, suggesting that the three indicators were given equal weight in the final summation. The decision to give equal weight to the three indicators was a subjective yet rational choice based on the fact that corrosion of the strand could occur due to chlorides and moisture reaching strands from two sources: (1) diffusion through concrete surface, and (2) entry thru interstitial spaces in between wires at the cut end of strand.

It is clear that among all beam-ends including those that were treated from the first day, the polymer resin coatings and the FRP wraps provided the smallest overall rating number (i.e. the best overall condition). The patch repair had the largest overall rating number (23), which indicated that the repair was not effective in its intended function. Among the beam-ends that were treated after 6 months of exposure, the FRP wrap had the best overall rating, followed closely by the polymer resin coating and epoxy coating. It is clear that protecting the beam-ends from day 1 is by far the best long-term approach. The untreated beam-end (2A) showed performance comparable to those of treated beam-ends after 6 months of exposure (except the patch repairs). As explained earlier, this is likely due to a noted electrical problem in this beam-end where loose connections may have moderated the effect of the accelerated corrosion process.

Considering that the cost and effort involved in installing FRP wraps, especially in existing structures, far exceed those of the polymer resin or epoxy coatings, it is recommended that polymer resin coatings or epoxy coatings be used instead.

Table 34. Comparison of various Beam-End Numerical Ratings and Overall Ratings*

| Beam End | Description | Chlorides | Cracking | Corrosion | Overall Rating |
|---|---|---|---|---|---|
| 1A | Epoxy Coated From Day 1 | 1 | 2 | 3 | **6** |
| 1B | Epoxy Coated After 6 Months of Exposure | 2.5 | 4 | 7 | **13.5** |
| 2A | No Treatment Applied | 2 | 6 | 5.5 | **13.5** |
| 2B | Patch Repair After 6 Months of Exposure | 8 | 7 | 8 | **23** |
| 3A | Silane Sealer Applied from Day 1 | 1 | 5 | 3.5 | **9.5** |
| 3B | Silane Sealer Applied After 6 Months of Exposure | 2 | 8 | 5.5 | **15.5** |
| 4A | Polymer Resin Coating Applied After 6 Months Exp. | 4.5 | 3 | 6 | **13.5** |
| 4B | FRP Wrap Applied After 6 Months of Exposure | 2.5 | 1 | 7 | **10.5** |
| 5A | Polymer Resin Coating Applied From Day 1 | 1 | 1 | 2 | **4** |
| 5B | FRP Wrap Applied From Day 1 | 1.5 | 1 | 2 | **4.5** |

*Individual criterion ratings were based on 1 –8 scale, 1 indicating best effect, 8 indicating worst effect. The overall ranking was based on a scale of 3 to 24 with 3 indicating the best condition and 24 indicating the worst condition.
Shaded rows indicate beam-ends that were treated after 6 months of exposure

*C h a p t e r 6*

# PROPOSED FIELD EVALUATIONS

## 6.1 FIELD EVALUATION PLAN

It is suggested that the treatment methods that were determined to be effective in this laboratory study be also evaluated on actual bridges in the field as part of a future study. It is proposed that the Wisconsin Department of Transportation identify a total of 10 to 15 candidate bridges for field demonstrations. Ideal candidates would consist of at least two to four pairs of new prestressed girder bridges. Each pair should be similar (preferably identical) and constructed in relative proximity to each other or on the same highway. Planning and allowance should be made in the contract drawings for localized surface treatments of the beam-ends (the last 2 ft) in one bridge in each pair using polymer resin coating or epoxy coating. These treatments should be applied before placement on the pads in the field so that all exposed surfaces within the coverage area are coated. The untreated bridges would serve as control bridges. The aesthetic issues involved in applications of coatings should be addressed, especially when the girders would be visible to the public from under the bridge. As a minimum, the color of the coating should be as close as possible to the untreated concrete. It is also possible to apply the treatment in a slightly larger area to provide a decorative pattern (perhaps an arch pattern) on the two exterior girder faces.

It is proposed that measurements be taken at yearly intervals. Such monitoring would include half-cell potential measurements and visual condition surveys (cracking, spalling, etc.). Since half-cell potential measurements cannot be performed over the coatings, it is suggested that a small, untreated opening (circular) be planned in the treatment area to allow half-cell measurements. The opening can have a cover to prevent chloride and moisture penetrations. However, steps must be taken to ensure that the opening does not affect or compromise the performance of coating.

In addition to the proposed treatments on new structures, it is also proposed that at least three pairs of existing bridges be identified as candidate bridges for evaluation of treatment applications on existing bridges. Each pair should be similar (preferably identical) and constructed in relative proximity to each other or on the same highway. It is recommended that these bridges be less than 15-20 years old to limit the pre-existing corrosion and chlorides in the beam-ends. The polymer resin coating or epoxy coating should be applied to the exposed areas of all beam-end in half of these bridges. Yearly half-cell measurements and surveys similar to those proposed for new bridges should be implemented. It is suggested that all these bridges be monitored for a time period of at least 5 to 10 years.

*Chapter 7*

# SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## 7.1 SUMMARY AND CONCLUSIONS

The primary objectives of this research were: (1) to collect and synthesize information on repair and rehabilitation methods for concrete bridges (2) to evaluate the effectiveness of preventative and corrective methods to address deterioration of prestressed bridge beam-ends and (3) to initiate development of an expert system software program to assist in the assessment, diagnosis, and repair of concrete bridges.

A thorough understanding of the state-of-the-art in the field of rehabilitation of concrete bridges, especially in northern climates, was considered crucial for the success of this effort. Therefore, a comprehensive review of available literature in relevant subject areas was performed. On-line sources of information, as well as conventional search databases were utilized. An extensive literature database was developed using Microsoft Access. Over 570 papers were cataloged, and include such searchable information as the title, publisher, author, and date. The database also includes the abstracts or summaries of many of the papers. The user can search the database by performing a keyword, title, or author query.

The following general conclusions can be drawn regarding the repair methods for concrete bridges based on the results of the literature review. A detailed discussion on each subject is given in chapter 2. Surface treatments, while reasonably effective over the short-term, have demonstrated limited effectiveness over the long term, unless they are applied prior to chloride contamination. Cathodic protection, while effective, is not commonly employed due to the high component and maintenance costs as well as the complexity of the method. In addition, due to the possibility of hydrogen embrittlement, cathodic protection of prestressed concrete beams is generally not recommended. Research studies have established the effectiveness of FRP composites to prevent and mitigate corrosion-damage in concrete columns.

An initial version of an expert system computer program, Concrete Bridge Assessment and Rehabilitation (ConBAR), was developed to assist in the diagnosis of concrete bridge deterioration problems and to identify repair, rehabilitation, or preventative maintenance options. This program includes a user-friendly interface that obtains relevant information on the subject bridge through a series of questions, and provides suggestions and recommendations to the user. The depth and variety of questions that ConBAR asks the user before making recommendations far exceed the scope of previous attempts at developing such expert system tools for concrete bridges. This necessitates a very large set of expert rules (based on combinations of possible answers) that must be incorporated into the program. This program currently includes the complete infrastructure required as well as a limited number of expert rules, which must be expanded and enhanced in future developments of this program. It is important to emphasize that the tools developed are intended and expected to assist and facilitate the work of experienced maintenance personnel, and not to replace it.

ConBAR addresses cracking, surface defects (such as honeycombing and blistering), spalling, corrosion, vehicle impact damage, alkali silica reactivity (ASR), and chemical exposure. The system also considers exposure conditions, previous repairs, bridge age, inspection information and other factors. The knowledge base includes: (1) facts and rules of thumb, (2) visual information such as photographs and drawings, (3) access to a rehabilitation literature database and (3) descriptive statements. ConBAR provides a number of possible solutions along with their pros and cons, a suggestion, or a hypothesis. Recommendations for additional tests or sources of information are supplied to confirm or refute the hypothesis.

Based on the results of the literature review, a test plan and repair concept were submitted and approved by the Project Oversight Committee, appointed by the project's sponsor, the Wisconsin Department of Transportation (WisDOT). The work plan included performing laboratory tests on five new 8-foot long prestressed concrete bridge I-beams to address corrosion-damage and subsequent repair of beams ends due to chloride-laden water infiltrating through faulty expansion joints. The beam-ends were subjected to wet/dry cycles of salt laden water to accelerate the corrosion process. In addition to the salt-water exposure, the beam-ends were subjected to an impressed electric current to assist in accelerated corrosion. Two "cathode" bars were placed in the beam and the entire reinforcement system (strands and bars) was made anodic. This created a "reverse cathodic protection" system, thus accelerating the penetration of chloride ions and the initiation of steel corrosion. Some end regions were pretreated with a sealer, epoxy coating, polymer (resin), or fiber-reinforced polymer (FRP) composite wrap to assess their effectiveness in protecting the beam when subjected to an accelerated corrosive environment.

As was done initially, sealer, epoxy coating, polymer (resin), and FRP wrap treatments were also applied to other previously untreated beam-ends after an initial exposure period of 6 months. In addition, one beam-end was patch repaired with no additional protection system to compare its performance with other systems. After the repairs were completed and the surface treatments applied, the beam-ends were again subjected to an accelerated corrosion regime. The overall exposure was extended from a period of 12 months to 18 months due to limited progress in initiating widespread corrosion in the beam-ends. A number of test parameters were measured during the monitoring period. The total accelerated corrosion exposure period for all specimens was 18 months.

The chloride content of the beams was determined prior to exposing the specimens to the accelerated corrosion environment, after the completion of 6 months of exposure, and after 18 months of exposure. The initial chloride content was measured in the middle area of one beam specimen. The chloride content was determined to be higher than expected. The mix water and aggregate sources used were then tested to identify the source of chlorides. It was determined that aggregates were the likely source. However, it is not clear, with the current level of testing, whether or not these chlorides are permanently bound within the aggregates. Chloride samples following the first 6 months of the accelerated corrosion regime were also taken at two locations on the bottom flange of the beam-end receiving the patch repair. The measurements indicated relatively high chloride concentrations near the surface, with the values decreasing with increasing distance from the surface. This is consistent with the behavior of chloride ions migrating into the concrete. The corrosion threshold was exceeded at all depths measured (up to 1 inch from the concrete surface) at a distance of 2 inches from the end of the beam. At the location of 6 inches from the face of the beam, the corrosion threshold level was exceeded up to a depth of ½ inch.

Chloride samples were also taken at all beam-ends at the conclusion of the entire 1 ½-year exposure prior to dissection. These measurements were made on samples taken in the middle of the sloping surface of the bottom flange at a distance of 2 inches from the back of the beam. The highest chloride levels were observed in the beam-end with patch repairs. It appears that the interface between the old and new concretes may have allowed accelerated intrusion of chlorides deep into the patch and old concrete. The chloride contents for the beam-ends that were treated with epoxy coating, polymer resin coating or FRP from the first day clearly show significantly lower chloride contents than other specimens. The beam-end treated with Silane sealer from the first day had far less chlorides than the untreated beams (or beams treated after 6 months). However, the chloride levels for this beam-end were higher than the corresponding beams treated with epoxy coating, polymer resin coating or FRP from Day 1. The specimens that were treated after 6 months show high levels of chlorides, but they are less than the beam with patch repair. Among the beam-ends that were treated after 6 months of exposure, the Silane sealer and the epoxy coatings had the least chloride contents.

A regulated voltage of 9V was applied continuously over the course of the exposure cycles to facilitate the corrosion process and speed the intrusion of chlorides. The corrosion currents versus time data for each of the beams were collected and recorded with a data acquisition system. All corrosion currents exhibit a decrease in value with time. This reduction is commonly observed in such experiments, and is due in part to the fact that corrosion products increase the resistance at the surface of strands. The cumulative area under the corrosion current versus time graph is indicative of the amount of steel loss due to corrosion. However, after careful examination of all results, it became clear that corrosion rate measurements were not an effective method for overall corrosion assessments in the localized beam-end areas. This may have been due to the fact that the measured corrosion rates were an indication of overall corrosion in the overall reinforcement system rather than the localized effect in the beam-ends.

In addition, periodically, half-cell potential readings were obtained. The half-cell measurements were only taken on the non-treated beam-ends since surface treatments provide a non-conductive barrier that renders the half-cell measurements ineffective. Expansion measurements were also periodically taken at each beam-end. However, due to problems encountered with the metal points corroding, the accuracy of the measuring device, and issues with keeping the points attached to the concrete surface, it was determined that the readings were inconsistent and not representative of accurate strain measurements. The specimens were also visually monitored for cracking and spalling. Detailed crack maps were sketched at the end of the first 6-month corrosion exposure cycle, and at the conclusion of all tests.

Half-cell measurements using a copper-copper sulfate electrode were obtained for each beam end. Initial half-cell potentials were relatively uniform at all points measured. Whereas the half-cell readings after the first exposure cycle varied, depending on their location on the beam. As expected, the values increased substantially as measurements neared the end of the beam. The highest readings were located on the bottom flange near the edge of the beam. These readings were consistent with the flow of the salt water down the end of the beam, which normally coincides with corrosion regions.

After six months of exposure to a corrosive environment, the half-cell readings for the untreated beam-end (opposite of the initially epoxy coated end) indicated that corrosion was not occurring. The half-cell readings for the four ends of the two initially untreated beams indicated that it was inconclusive whether or not corrosion was occurring. However, the untreated beam-end (opposite of the initially sealed end) possessed some half-cell readings on the bottom flange outer corner that indicated that there was 90% likelihood that corrosion was occurring at these regions.

After 10 months of exposure, the patched beam-end yielded a higher potential in comparison to the untreated end. The half-cell readings for the patched end were large enough to fall into the category that, with 90% probability, corrosion was likely occurring. Whereas the readings for the untreated end indicated that it could not be determined whether or not corrosion was occurring. It was concluded that, the higher potential indicated that the likelihood of corrosion occurring in the patched end is greater than in the untreated end. The half-cell potential readings for beam ends 2A (no treatment) and 2B (patched) after 18 months of exposure clearly showed corrosion activity in the beam-ends.

At the completion of the first exposure cycle all beam-ends had heavy salt residue along the front faces and on some portions of the bottom flanges. Rust stains were also evident along the path of the salt water. No major spalling or cracking was observed at that time. Some flaking of concrete was observed at the corners of the beam. In addition, corrosion products were observed on the exposed tendon ends, and were found to increase in amount over the course of the exposure. Since the first 6-month exposure cycle did not result in the concrete spalling or significant tendon corrosion, the configuration of the saltwater dispersion system was altered slightly to increase the likelihood of corrosion. The altered salt-water distribution setup was able to disperse water to both the sides and face of the beams. An 18-inch long concrete region of one of the untreated beam-ends was removed with a chipping hammer to facilitate installation of the patch repair Corrosion products were observed mainly at the end regions of the tendons. The build-up of corrosion products was seen to decrease as the distance from the edge of the end increased.

At the end of the 18-month exposure period, the beams were experiencing significant rust staining and salt residue deposits. Cracking was evident in many beam-ends. All beam-ends were crack-mapped and subsequently partially dissected. The state of corrosion of strands in each beam-end was numerically classified. The final decision on effectiveness of various methods was based on numerical ratings given to three indicators: chloride content, extent of cracking, and extent of observed strand corrosion. Each of the three parameters was given equal weight in determining the overall ratings. The following table illustrates the final ratings given.

Table 34. Comparison of various Beam-End Numerical Ratings and Overall Ratings*

| Beam End | Description | Chlorides | Cracking | Corrosion | Overall Rating |
|---|---|---|---|---|---|
| 1A | Epoxy Coated From Day 1 | 1 | 2 | 3 | **6** |
| 1B | Epoxy Coated After 6 Months of Exposure | 2.5 | 4 | 7 | **13.5** |
| 2A | No Treatment Applied | 2 | 6 | 5.5 | **13.5** |
| 2B | Patch Repair After 6 Months of Exposure | 8 | 7 | 8 | **23** |
| 3A | Silane Sealer Applied from Day 1 | 1 | 5 | 3.5 | **9.5** |
| 3B | Silane Sealer Applied After 6 Months of Exposure | 2 | 8 | 5.5 | **15.5** |
| 4A | Polymer Resin Coating Applied After 6 Months Exp. | 4.5 | 3 | 6 | **13.5** |
| 4B | FRP Wrap Applied After 6 Months of Exposure | 2.5 | 1 | 7 | **10.5** |
| 5A | Polymer Resin Coating Applied From Day 1 | 1 | 1 | 2 | **4** |
| 5B | FRP Wrap Applied From Day 1 | 1.5 | 1 | 2 | **4.5** |

*Individual criterion ratings were based on 1 –8 scale, 1 indicating best effect, 8 indicating worst effect. The overall ranking was based on a scale of 3 to 24 with 3 indicating the best condition and 24 indicating the worst condition.
Shaded rows indicate beam-ends that were treated after 6 months of exposure

## 7.2 RECOMMEDATIONS

Based on the results of this research effort, the following recommendations are made:

- The most effective solution for protection of prestressed concrete beam-ends is determined to be treating the beam-ends from the first day, i.e. before installation in the field. The treatment area would be limited to all surfaces within a 2-ft-length at the two ends of each beam. This includes the back end surface and the bottom surface. When the strands are cut flush with the back of the beam, the treatment must cover the cut end well to prevent horizontal migration of chlorides through interstitial spaces between wires. In cases where the strands are not cut flush (i.e. embedded in the diaphragm concrete), the exposed strand must be coated well to prevent horizontal chloride migration. This approach (treatment from the first day) is far more effective, and easier, than subsequent treatments in the field. The carbon fiber-reinforced polymer (FRP) coating, and polymer resin coating (FRP without fiber) were found to be the most effective treatments. Epoxy coating was the next best solution followed by silane treatment. As expected, leaving the beam-end untreated resulted in the worst overall performance compared to beam-ends that were treated from day 1.

- Considering that the FRP wrap, polymer resin coating, and epoxy coating were generally effective, it is recommended that either polymer (resin) coating or epoxy coating be used in new construction to protect the prestressed concrete beam-ends. The FRP wraps did not significantly improve performance over polymer resin coating, and would only add to the cost and difficulty of treatment. Since protecting the end face of the beam and the cut ends of the strands are crucial, it is recommended that such treatments be performed in advance of installation in the field. The presence of diaphragms, bearings or other obstructions would likely make the field application of coatings to the beam-ends very difficult; especially after the diaphragm and deck concrete is cast.

- For existing prestressed concrete beam-ends, it is recommended that the protective treatments be applied as soon as possible, before chloride levels increase significantly. It is expected that the applications of polymer resin coating or epoxy-coatings to the exposed surfaces of the beam-ends in the field would contribute, albeit not as effectively, to the protection of beam-ends in the long run, if such treatments are implemented before chloride contaminations and corrosion have taken hold. In such cases, all exposed surfaces should be treated with either polymer resin coating or epoxy coating. The extent of pre-existing chloride contamination can be measured in the field (on the bottom flange at about 2 inches from the end of the beam) and compared with chloride contents measured in areas not exposed to chloride contaminations.

- In cases where corrosion and damage is advanced and has resulted in cracking and spalling of the beam-ends, the conventional patching alone would likely not be a durable repair method. Although not tested in this experimental effort, a patch repair that is subsequently coated with polymer resin coating or epoxy coating would likely provide a more effective repair.

- Although the above results and recommendations were based on tests on beam-ends, it is expected that they would also be applicable to pier elements (such as pier caps and columns) and abutments.

- The development of the ConBAR expert system program should be continued to include additional decision rules, deterioration cases and repair methodologies.

- The developed repair database should be continuously augmented and perhaps incorporated into ConBAR.

- The proposed field investigation detailed in Chapter 6 of this report should be considered for implementation.

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